# Numerical Weather Prediction

## Flooding at Boscastle, Cornwall on 16 August 2004 – A study of Met Office Forecasting Systems

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## Executive summary

During the afternoon of Monday 16 August 2004, heavy rainfall brought flash flooding to the village of Boscastle on the north Cornish coast. Around 60 properties were flooded, over 100 people were rescued by helicopter and many vehicles were washed into the harbour.

This report reviews the performance of Met Office operational and experimental systems in forecasting the heavy rainfall that generated the flooding on 16 August 2004.

**The conclusions of this review can be summarised as follows:**

- Observations show that maximum precipitation reaching twice the monthly average rainfall for North Cornwall, was observed in a narrow strip of about 4km by 10km. Due to its intensity and very small size, this event was an extreme test of Met Office operational and experimental precipitation forecasting systems.

- The Nimrod and Gandolf nowcast schemes failed to adequately predict the event because it did not fit the pattern of a rain band or rain cells moving unchanged with constant velocity. Rather, the situation was characterised by continual development of new cells, a process for which nowcasting methods are not suited. In Nimrod and Gandolf, such development is included by merging downscaled information from the mesoscale NWP model, a process which is normally very successful in extending the useful forecast period. However, on this occasion, the event was too small to be resolved by the NWP model.

- The new, STEPS, ensemble nowcast provided few advantages over Gandolf and Nimrod nowcasts for the same reasons that Nimrod and Gandolf performed poorly. The incorporation of a stochastic, convective initiation and life cycle model algorithm into STEPS, similar to that implemented in the Convection Diagnosis Procedure (CDP), may go some way towards the effective handling of extreme, yet very localised events such as that which occurred in the vicinity of Boscastle on 16$^{th}$ August 2004. The vast majority of fluvial flood events are caused by much larger scale pluvial events than that which occurred on 16 August 2004. For example, the Easter floods of 1998 were associated with a broad band of slow moving precipitation containing numerous embedded, intense precipitation cores associated with convective cells. STEPS can be expected to add significant value to mesoscale NWP output in these more common flood producing precipitation events.

- The Convection Diagnosis Procedure (CDP) provided useful guidance on the structure of the convection. However, the outputs need careful interpretation and the signal for the rainfall rates was weak.

- A 4-km grid length mesoscale NWP simulation was able to generate storms that produced high rainfall accumulations remarkably close to where they occurred, when the equivalent 12-km operational forecast was unable to give any direct warning of such an event. The reason the 4-km model could do this was because it could explicitly resolve the thunderstorms instead of having to rely on a convection scheme, and, equally importantly, was able to resolve the complex flow around the coast which lead to repeated triggering of storms in the same place. Two successive forecasts produced very consistent results, though the first was better. This suggests that the event had a high degree of predictability but small scale uncertainty was still enough to make the forecast unreliable at the scale of the Boscastle catchment.

- A 1-km grid length forecast produced an even better location for the high accumulations because it was able to resolve the showers and the local orography more accurately. Lower (though still high) accumulations were produced than the 4 km model, which reflects a known problem with the 4 km model.

- The mesoscale NWP model confirms that the interpretation of the mechanism leading to such spatial localisation publicised at the time appears to be substantially correct. This mechanism involves strong low level convergence at the coast due to land-sea roughness and thermal contrast, modulated strongly by local orography, leading to a very specific and repeating location for triggering of storms.

- The output from the 4-km mesoscale NWP forecast represents a specific realisation of the event, which we know is going to be in error to some extent. If we took the later, 03 UTC, forecast literally it would warn of the high rainfall totals falling into a different river catchment to the one it did fall into. It is possible to be misled into believing the detail unless we have a good understanding of the uncertainty in NWP forecasts. Since many customers do not have that appreciation, it is vital that we present the output in a way that shows some uncertainty yet picks out the more reliable and important information.

- The mesoscale NWP products shown in Section 4 of this report show that the model was suggesting a risk of high rainfall totals but without being specific about exactly where the rain would occur. At best, a warning of flash flooding in the N Cornwall and N Devon areas could have been supported. Two issues that need addressing are (1) how we determine the spatial accuracy of precipitation forecasts so that diagnostic products can be tuned to those scales and (2) whether there are ways of determining how predictable forecasts are likely to be on a particular day (beyond use of expensive ensembles). On this occasion, it is likely that the storms were reasonably predictable because there was a strong coastal and orographic component to the forcing. On other days, however, the atmosphere may be much less predictable. We would like to have products that reflect this.

- This event has added weight to the belief that an NWP model with 4-km grid length or better, with appropriate output products, has the potential to provide significantly more useful short-range predictions of high-impact rainfall events than is currently possible.

- There is a need to clarify the relationship among the different very short range nowcasting and forecasting schemes to ensure that the most appropriate outputs are used. High resolution NWP will not meet this need alone.

**The following recommendations are made as a result of this review:**

- A stochastic convective initiation and life cycle model algorithm, similar to that implemented in the Convection Diagnosis Procedure (CDP), should be incorporated into STEPS. This may go some way towards the effective handling of extreme, yet very localised events.

- Outputs from the Convection Diagnosis Procedure (CDP) should be reviewed to ensure that the products are useful to forecasters.

- 'High resolution' NWP is able to produce realistic convective storms which respond to surface forcing and give more useful indication of peak rainfall than parameterized convection in lower resolution models. 4 km is only a marginally adequate resolution, while 1 km is a worthwhile target resolution. High resolution NWP should therefore be adopted as soon as resources allow.

- A post-processing system for high resolution NWP needs to be developed to provide appropriate risk-based inputs to downstream flood warning processes. This should be in the form of probabilistic guidance which allows for the positional and developmental uncertainties inherent in model forecasts.

- Longer trials of NWP systems are required to calibrate post-processing systems.

- A new post-processing system is required to rationalise the capability currently provided by Nimrod, Gandolf and CDP systems. It may be appropriate to introduce this with the implementation of the 4km UK NWP model in 2005.

- Introducing a spatially varying B parameter, depending on at least a topographic index, should be considered as a development task for Nimrod-MOSES-PDM.

- A more accurate 5km land-sea mask should be sought for Nimrod. The original code for generating the land-sea mask should be checked for correct registration of the AVHRR data and the criterion for a land Nimrod square should be changed from 50% of land in the square to a lower value, perhaps 25%.

## 1.0 Introduction

During the afternoon of Monday 16 August 2004, heavy rainfall brought flash flooding to the village of Boscastle on the north Cornish coast. Around sixty properties were flooded from the rivers Valency, Jordan and Paradise, some being completely destroyed. Over 100 people were rescued by helicopter and many vehicles were washed into the harbour. Fortunately there appears to have been no loss of life. Examples of the impact of the flood are shown in Figure 1.

**Figure 1 Photographs showing the aftermath of the floods (Source: Environment Agency)**

On 16 August 2004, southwest England was on the forward side of a slowly deepening area of low pressure. Surface analysis charts for 0000UTC, 0600UTC, 1200UTC and 1800UTC on 16 August 2004 are shown in Figure 2. Although the surface air mass was not characterised by the very high humidity that had been experienced during the previous week, 850 hPa wet-bulb potential temperatures were nonetheless relatively high at about 15°C.

In the early hours of 16 August 2004, an extensive area of heavy convective precipitation developed in the English Channel and moved north-eastward over south-west England. From late morning, a line of convective cells developed downwind of high ground about 20km south-south-west of Boscastle. Between 1100UTC and 1700UTC intense convective cells were repeatedly generated and moved down wind before gradually decaying.

Cobbacombe radar 2km resolution accumulations show a plume of intense rainfall about 4km across and 10km long, with maximum accumulations of 134mm at the top of the Valency catchment in the 7 hour period from 1100UTC to 1800UTC on 16 August 2004. A rain gauge at Trevalec, Lesnewth, fairly close to the location of this maximum, recorded 181mm in five hours during this event. This represents almost twice the monthly long term average rainfall for August in north Cornwall of 95mm.

Due to its intensity and very small scale, this event provides an extremely demanding test of the Met Office's forecasting systems. The main operational guidance tool for UK forecasting is the mesoscale configuration of the Unified Model, which has a grid length of about 12.3km. This is unable to resolve rainfall features smaller than about 50km across, so a variety of complementary systems has been developed to provide additional forecast information. These include the nowcasting systems, Nimrod and Gandolf, and the convective diagnosis procedure, CDP. Future developments in this area are focussed on the STEPS ensemble nowcasting scheme. Beyond a few hours ahead, progress depends on use of finer resolution NWP models, and research is in progress on the use of 4km and 1km grid length versions of the Unified Model. The Met Office also has a suite of hydrological models associated with the Nimrod nowcast system, which have the potential for providing guidance on soil moisture and runoff. The remainder of this paper reports on the evaluation

of these forecasting systems: identifying the limitations of existing operational systems, and assessing the potential contribution of the experimental systems being developed for future implementation.

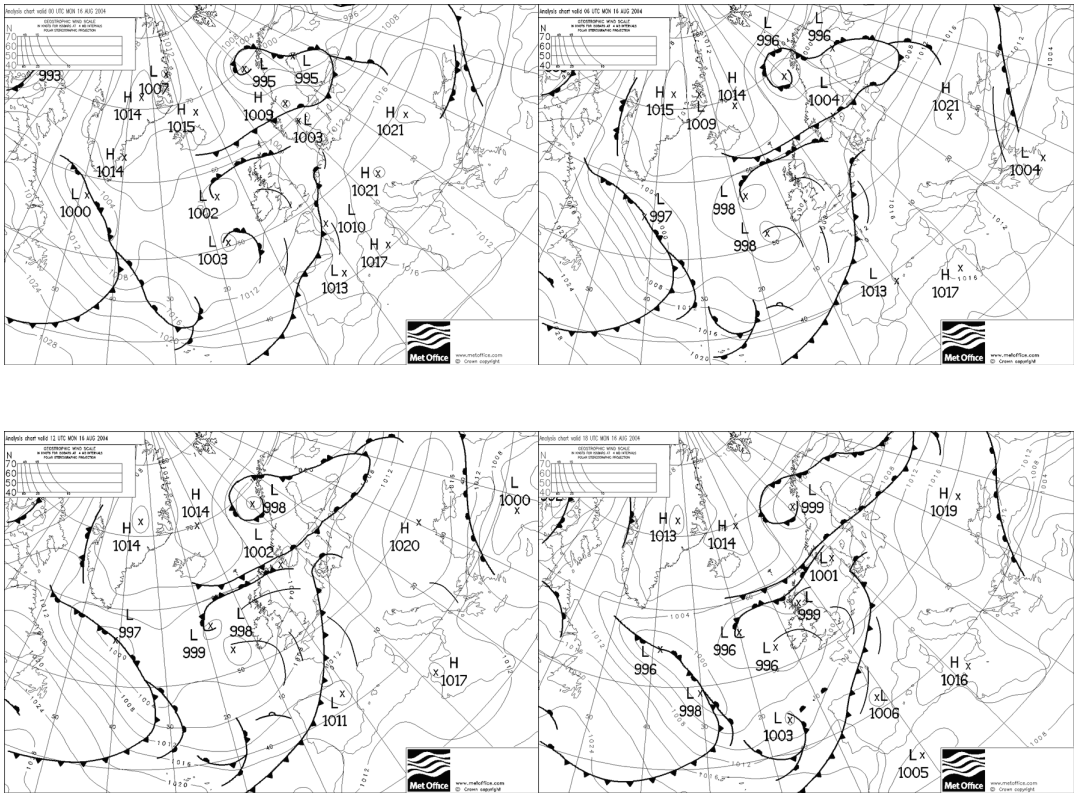

Figure 2 Surface Analysis Charts for 0000 UTC, 0600 UTC, 1200 UTC & 1800 UTC on 16 August 2004

## 2.0 Appraisal of operational and experimental nowcast products

### 2.1 Overview of the Met Office's precipitation nowcasting systems

Although Numerical Weather Prediction (NWP) models are the primary source of weather forecast guidance in the Met Office, they remain insufficiently accurate to provide routinely useful, very short range (up to six hours ahead), quantitative predictions of precipitation at high spatial (≤ 5km) and temporal (< 1 hour) resolutions. Precipitation nowcasting techniques seek to address this deficiency by making optimal use of a range of observational and NWP data sources, in combination with a conceptual knowledge of the behaviour of small (sub-grid) scale weather phenomena.

#### 2.1.1 Deterministic models: Nimrod and Gandolf

The Met Office runs several automated nowcasting systems operationally. These are known as Nimrod (Golding 1998; see figure 1) and Gandolf (Pierce *et al*. 2000). Both systems incorporate Quantitative Precipitation Nowcast (QPN) algorithms tailored to the needs of the fluvial flood prediction authorities in England and Wales (the Environment Agency). These systems blend relatively coarse resolution (~12 km) rainfall forecasts from the Met Office's mesoscale NWP model (hereafter the Mesoscale Model [MM]) with finer resolution, observation based extrapolation (advection) nowcasts.

The starting point for a QPN is an analysis of instantaneous rain rate assimilated from radar, satellite and surface precipitation observations, and a previous nowcast. The radar data are the primary source of information over England and Wales. They are subject to a series of quality control and correction procedures designed to remove spurious (non-precipitation) echoes and convert the radar observed reflectivity to a best estimate of precipitation rate at the surface. Corrections (Smith and Kitchen 1998) include a vertical profile correction designed to account for the effects of the bright band and orographic enhancement, and a rain gauge-based mean field bias adjustment. The latter ensures that the derived surface field is consistent with rain gauge measurements. The rain analysis is an inverse error variance weighted combination of the various inputs.

The extrapolation scheme implemented within Nimrod utilises a combination of two advection algorithms: an object-oriented cross correlation technique similar to TREC (Rhinehart and Garvey 1978), and NWP model wind advection. The choice of advection scheme may vary from rain area to rain area depending upon the relative performance of hindcasts generated using each of these schemes in turn. Recent developments in optical flow theory derived from work in the field of computer vision (Horn and Schunck 1981) form the basis for the advection scheme in Gandolf. This scheme relies upon a solution of the optical flow constraint equation (Bowler and Pierce 2002) and has similarities with the variational echo tracking scheme proposed by Laroche and Zawadzki (1994).

The Gandolf system also incorporates several conceptual life cycle models of convection. These models represent the evolution of convective cells (shower clouds) and their associated precipitation in terms of five developmental stages. These stages are distinguished by their vertical reflectivity profiles, retrieved from multi-beam radar reflectivity observations. A forecast algorithm allows each observed convective cell and its associated attributes to proceed through an idealised evolutionary cycle determined by one of three conceptual life cycle models: *single cell*, *multi-cell* or *supercell* (Pierce and Cooper, 2000). Cells are advected by a representative NWP model wind vector. A key component of the *multi-cell* model is an algorithm designed to simulate severe storm propagation by daughter cell generation (Hand 1996).

Gandolf heavy rainfall warnings take the form of five minute, coded text messages. They are transmitted to the Environment Agency at 0, 5, 10, .. , 55 minutes past each hour. Each Warning Message comprises two or three parts: a date-time stamp, an *alert status*, and an Expected Time of Arrival (ETA) for forecast precipitation (optional). The *alert status* can either be a number (**0–9**) or a letter (**A–H**). Its value depends upon three things: whether precipitation is convective or dynamic, the forecast depth of accumulation, and the forecast lead time. Table 1 shows a contingency table used to compute the *alert status*.

Warnings are issued for each catchment area specified by the Environment Agency. Currently, these catchment areas broadly equate to Environment Agency regions rather than individual river catchments.

**Table 1 Contingency table for warning message *alert status*.**

| Weather type | Forecast lead time / minutes | Forecast accumulated precipitation in one hour / mm | alert status |
|---|---|---|---|
| 1 (dynamic) or 3 (dyn.+conv.) | > 180 | 0.0 | 0 |
| | | < 4.0 | A |
| | | 4.0 - 8.0 | B |
| | | 8.0 - 16.0 | C |
| | | 16.0 - 32.0 | D |
| | <= 180 | 0.0 | 0 |
| | | < 4.0 | E |
| | | 4.0 - 8.0 | F |
| | | 8.0 - 16.0 | G |
| | | 16.0 - 32.0 | H |
| 2 (convective) | > 180 | 0.0 | 0 |
| | | < 4.0 | 1 |
| | | 4.0 - 8.0 | 2 |
| | | 8.0 - 16.0 | 3 |
| | | 16.0 - 32.0 | 4 |
| | <= 180 | 0.0 | 0 |
| | | < 4.0 | 5 |
| | | 4.0 - 8.0 | 6 |
| | | 8.0 - 16.0 | 7 |
| | | 16.0 - 32.0 | 8 |
| | | > 32.0 | 9 |

### 2.1.2 Stochastic models: the CDP and STEPS

At present, a single, best guess precipitation nowcast is generated by the Gandolf and Nimrod systems. The quality of these best guesses can vary significantly with the nature and extent of observed precipitation. On-going research and development in the Met Office aims to quantify the uncertainties and errors in QPNs and convey these to the end user (Pierce *et al.* 2004). Several approaches have been explored. These are embodied in the Convection Diagnosis Project (CDP; Hand 2002) implementation and the Short-Term Ensemble Prediction System (Bowler *et al.* 2004). The CDP can be considered an operational system whereas the Short-Term Ensemble Predication System is not.

The aim of the CDP is to provide probabilistic guidance on the intensity, distribution and duration of showers over the UK for the period out to T+36 hours. MM forecasts are post-processed to consider the influence of unresolved, sub-grid scale, near surface forcings on

the initiation of free convection, and the subsequent evolution of convective precipitation. The probability forecasts produced account for errors in the pertinent variables forecast by the MM.

The Short-Term Ensemble Prediction System (STEPS), developed jointly by the Met Office (Joint Centre for Hydro-Meteorological Research) and the Bureau of Meteorology (Bureau of Meteorology Research Centre), is a spectral model that considers the temporal evolution of precipitation fields on a hierarchy of spatial scales (Bowler *et al*. 2004). It exploits the precipitation nowcast modelling frame embodied by Nimrod (involving the blending of an advection forecast with a NWP forecast), but also considers the uncertainties in the diagnosed advection velocities, and the errors in the predicted temporal evolution of rain rate.

A stochastic advection forecast is produced by adding a perturbation to the diagnosed advection velocity field. In a forecast sequence, stochastic noise with a power spectrum conditioned on that of the latest *rain analysis* replaces advected precipitation features beyond their estimated temporal limits of predictability (persistence in a Lagrangian reference frame). A single forecast realisation is produced by blending this stochastic advection forecast with a time synchronous rainfall forecast from the MM. The relative weights given to the advection forecast, the NWP forecast and the stochastic noise depend upon the relative skill of the advection and NWP components, as measured against a recent *rain analysis*, and on the fraction of the observed variance (in the *rain analysis*) represented by the NWP forecast on a hierarchy of scales.

The resultant forecast is one in which stochastic noise with a distribution conditioned on that of the latest *rain analysis* replaces advected precipitation with advancing lead time. Owing to the dynamic scaling properties of precipitation this process proceeds from the smallest scales upwards (these are the least predictable), but is arrested by the predictive skill of the NWP model forecast with which it is blended.

## 2.2 Pertinent aspects of the meteorology in relation to nowcast model performance

As described in Section 2, an extensive area of heavy convective precipitation developed in the English Channel from the early hours of 16 August 2004, and moved north-eastward over south-west England. From mid-morning, the convection became organised into a series of bands propagating in a north-easterly direction. Analysis of five minute, 2 km resolution radar data from Cobbacombe Cross shows that there were favoured regions for the initiation of new convective cells. These correlated well with areas of elevated topography exposed to the prevailing wind.

From around 1100 UTC, a pronounced line of convective cells developed down wind of high ground about 20 km south-south-west of Boscastle. The favoured zone of initiation was the elevated topography extending north-eastwards of the Camel estuary. Here the ground rises abruptly from several tens of metres above MSL to between 150 m and 300 above MSL. Between 1100 UTC and 1700 UTC this area saw repeated initiation of intense convective cells, which subsequently moved downwind at speeds between 30 km $h^{-1}$ and 50 km $h^{-1}$ (estimated from 5 minute sequences of Cobbacombe Cross radar data), and gradually decayed. During this six hour period, peak, grid square (2 km) mean instantaneous rain rates estimated from the Cobbacombe Cross weather radar routinely exceeded 100 mm $h^{-1}$. Estimates of surface rain accumulation from the same source exceeded 128 mm over the 7 hour period in the vicinity of Otterham (O.S. NG ref. 216800 m E, 90600 m N) between 1100 UTC and 1800 UTC inclusive. With representivity error in

mind, this compares well with a 24 h total for the 16 August of 200.4 mm reported by an Environment Agency rain gauge in Otterham village.

Scrutiny of the 1200 UTC radiosonde ascent from Cambourne shows that substantial (though not unusual) Convectively Available Potential Energy (CAPE) could be released upon initiation of surface forced convection in Cornwall (~217 J $kg^{-1}$ virtual CAPE). The vertical profile of the horizontal wind shows substantial speed shear (see figure 4), but only limited directional shear, this being largely confined to the lowest kilometre or so. This scenario is marginal in terms of its potential for supporting multi-cell storm evolution, since directional shear of ≥ 45 degrees (between wind vectors at the heights of cell low level inflow and upper level outflow) is normally required for the effective separation of updraughts and downdraughts and the initiation of daughter cells (Pierce and Cooper, 2000). Close scrutiny of the available high resolution radar data suggests that the event was largely characterised by the repeated formation of intense, non-severe convective cells over a few favoured areas of elevated topography. Newly formed storms were then advected down-wind and weakened as they became detached from these localised convergence zones.

The emerging picture of an event dominated by local, surface based orographic forcing is supported by evidence from the operational, ~12 km resolution Mesoscale Model (MM) and the experimental, ~4 km UK NWP model. MM forecasts of instantaneous rain rate for the afternoon of 16 August show little or no large scale organisation, hence forcing of the precipitation. By contrast, comparable runs of the ~4km UK NWP model appear to have captured, at least in part, the two key attributes of the event, namely its severity and local nature.

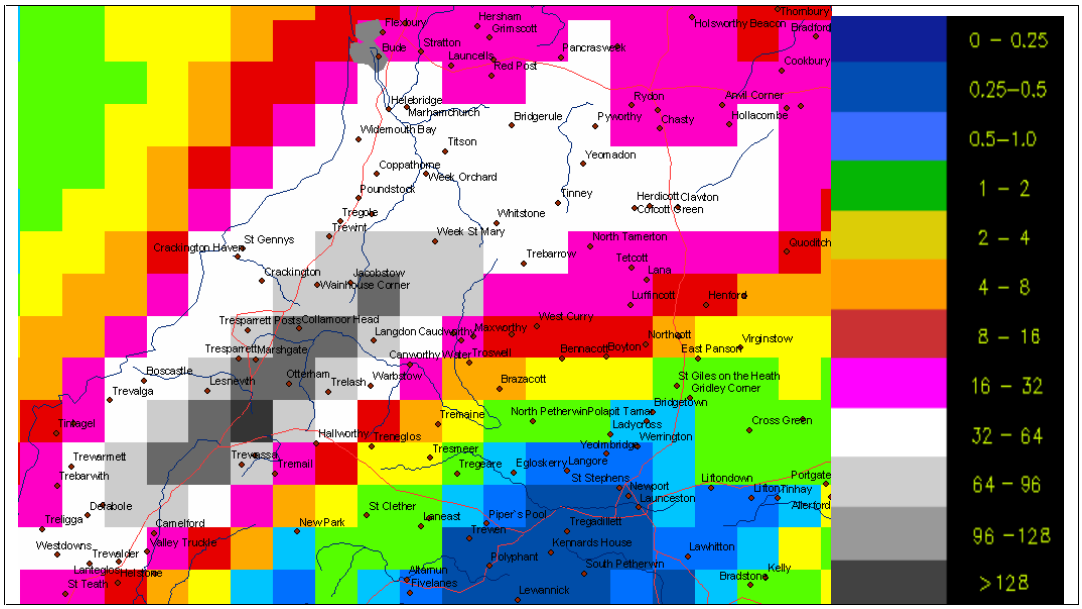


**Figure 3 Surface rain accumulation estimated from Cobbacombe Cross weather radar data (2 km) for the period 1100UTC to 1800UTC on 16 August 2004**

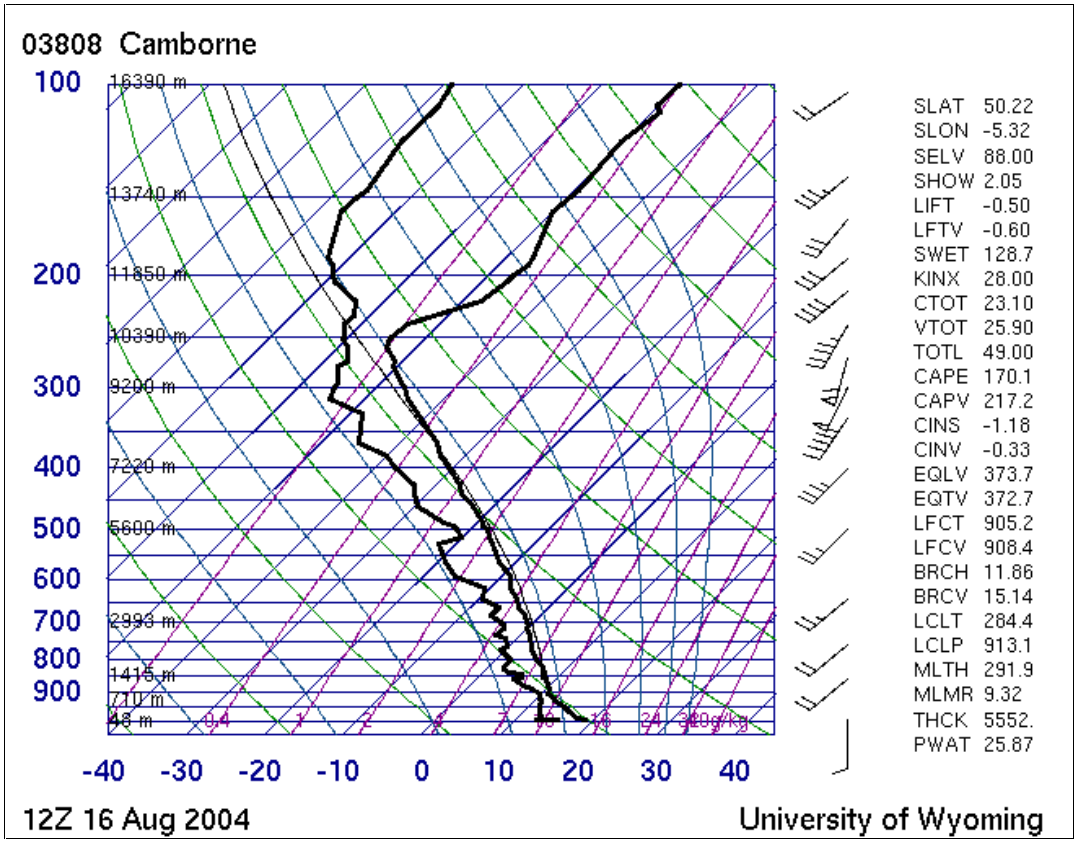


Figure 4 Upper air sounding from Cambourne, 1200UTC, 16 August 2004

## 2.3 Performance of operational Gandolf and Nimrod deterministic nowcasts

The performance of Gandolf's precipitation nowcast algorithms has been assessed by examining a range of forecasts run throughout the day on 16 August 2004. Figure 6 compares T+1, T+3 and T+6 h forecasts of instantaneous rain rate from the 1300 UTC run with best estimates of surface instantaneous rain rate from the Cobbacombe radar. The 1300 UTC run shown here is typical of the performance of Gandolf on the day.

As explained in section 3.1.2, Gandolf can run one of several forecast algorithms on a given area of precipitation: an optical flow based advection scheme, or an object-oriented convective life cycle model comprising models for single cell, multi-cell and supercell convection. The system is tuned such that the life cycle modelling approach is only used in cases of severe multi-cell, or supercell convection, when previously published case studies (e.g. Hand 1996, Pierce and Cooper 2000) have shown it to produce superior forecasts of convective precipitation to those produced by linear extrapolation.

On the 16 August the optical flow advection scheme was used in preference to life cycle modelling because the atmospheric conditions were assessed to be unfavourable for the generation and maintenance of multi-cell or supercell convection. The key factor in this decision was the absence of sufficient directional vertical wind shear which is required for the maintenance of severe convection.

Linear extrapolation schemes, including the optical flow scheme, are well suited to diagnosing the motion of slowly evolving, large scale precipitation events. In cases of convective precipitation, particularly localised convection, the observed rapid changes in the

distribution of rain rate can give rise to unreliable extrapolation velocities that reflect both genuine motions, and apparent motions due to heterogeneous growth and decay.

On the 16 August, the Gandolf extrapolation scheme diagnosed velocities that captured the average, apparent motions of the precipitation areas in south-west England successfully. The resulting extrapolation forecasts quickly advected the convective precipitation over Boscastle and the head waters of the River Valency away to the north-east. The MM component of the same Gandolf forecasts failed to predict the local re-generation of convective cells in the vicinity of Boscastle. Consequently, Gandolf forecasts were unable to maintain heavy precipitation within the Valency catchment area.

Similar results were found for Nimrod nowcasts made between 1100 UTC and 1500 UTC on 16 August 2004. The 1300 UTC nowcast of rain rate is shown in figure 7. In common with the performance of Gandolf, the Nimrod extrapolation scheme moved the intense precipitation over north Cornwall away to the north-east. As previously described, the MM component was unable to predict the location or intensity of the precipitation in the vicinity of Boscastle. The overall effect was a failure to capture the severity and local nature of the event.

## 2.4 Performance of operational Gandolf heavy rainfall warnings

Despite the failings of Nimrod and Gandolf nowcasts, the 5 minute heavy rainfall warning messages issued automatically by the Gandolf system to the Environment Agency on 16 August 2004 were of value, although not sufficiently specific in terms of threat area to allow warnings to be issued for Boscastle and the Valency catchment. A excerpt from the Gandolf heavy rainfall warning messages log is shown in figure 5a. See section 3.1.1 for further information on this system including a contingency table used to compute the *alert status*.

Each warning message contains an encoded prediction of the maximum, pixel based (2 km by 2 km square) hourly accumulation predicted anywhere within a specified region (in this case, the Environment Agency's south-west region) in the next 24 hours. This maximum accumulation is based upon Gandolf forecasts out to T+6 h, and beyond this, MM forecast accumulations.

Warnings began to be generated by the Gandolf system during the morning of 16 August 2004. Then during the afternoon, the warnings issued from 1550 UTC onwards indicated that in excess of 32 mm accumulation (the highest possible warning) could be expected in the next hour. The trigger for this warning was the heavy rain advected down wind of Boscastle by the Gandolf advection scheme (see figure 5b).

## 2.5 Performance of non-operational STEPS 50 member ensemble

STEPS has a number of potential advantages over Nimrod and Gandolf. It considers the impact of errors in the diagnosed extrapolation velocities and the extrapolation forecast of rain rate on the resultant rain rate distribution. It also accounts for the failure of the MM to resolve the near grid and sub-grid scale distribution of rain rate by downscaling the MM forecast precipitation fields. The uncertainties in the predicted distributions of rain rate and rain accumulation are expressed in ensemble form.

On the 16 August, STEPS provided few advantages over Gandolf and Nimrod nowcasts. This was chiefly because the event in question was too small to be resolved by the MM. In this situation, the downscaling of MM precipitation is of no benefit. The incorporation of a

stochastic, convective initiation and life cycle model algorithm into STEPS, similar to that implemented in the CDP, may go some way towards the effective handling of extreme, yet very localised events such as that which occurred in the vicinity of Boscastle on the 16 August 2004. The vast majority of fluvial flood events are caused by much larger scale pluvial events than that which occurred on 16 August 2004. For example, the Easter floods of 1998 were associated with a broad band of slow moving precipitation containing numerous embedded, intense precipitation cores associated with convective cells. STEPS can be expected to add significant value to mesoscale NWP output in these more common flood producing precipitation events.

```
GANDOLF warning at 16.08.04 12:30:03 GMT. ALERT status is 7. Precipitation expected by 1230 GMT.
GANDOLF warning at 16.08.04 12:35:01 GMT. ALERT status is 7. Precipitation expected by 1235 GMT.
GANDOLF warning at 16.08.04 12:40:02 GMT. ALERT status is 7. Precipitation expected by 1240 GMT.
GANDOLF warning at 16.08.04 12:45:03 GMT. ALERT status is 7. Precipitation expected by 1245 GMT.
GANDOLF warning at 16.08.04 12:50:02 GMT. ALERT status is 7. Precipitation expected by 1250 GMT.
GANDOLF warning at 16.08.04 12:55:02 GMT. ALERT status is 7. Precipitation expected by 1255 GMT.
GANDOLF warning at 16.08.04 13:00:02 GMT. ALERT status is 7. Precipitation expected by 1300 GMT.
GANDOLF warning at 16.08.04 13:05:02 GMT. ALERT status is 7. Precipitation expected by 1305 GMT.
GANDOLF warning at 16.08.04 13:10:02 GMT. ALERT status is 7. Precipitation expected by 1310 GMT.
GANDOLF warning at 16.08.04 13:15:02 GMT. ALERT status is 7. Precipitation expected by 1315 GMT.
GANDOLF warning at 16.08.04 13:20:02 GMT. ALERT status is 7. Precipitation expected by 1320 GMT.
GANDOLF warning at 16.08.04 13:25:02 GMT. ALERT status is 7. Precipitation expected by 1325 GMT.
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GANDOLF warning at 16.08.04 13:50:01 GMT. ALERT status is 7. Precipitation expected by 1350 GMT.
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GANDOLF warning at 16.08.04 14:05:02 GMT. ALERT status is 7. Precipitation expected by 1405 GMT.
GANDOLF warning at 16.08.04 14:10:02 GMT. ALERT status is 7. Precipitation expected by 1410 GMT.
GANDOLF warning at 16.08.04 14:15:02 GMT. ALERT status is 7. Precipitation expected by 1415 GMT.
GANDOLF warning at 16.08.04 14:20:03 GMT. ALERT status is 7. Precipitation expected by 1420 GMT.
GANDOLF warning at 16.08.04 14:25:04 GMT. ALERT status is 7. Precipitation expected by 1425 GMT.
GANDOLF warning at 16.08.04 14:30:04 GMT. ALERT status is 7. Precipitation expected by 1430 GMT.
GANDOLF warning at 16.08.04 14:35:02 GMT. ALERT status is 8. Precipitation expected by 1435 GMT.
GANDOLF warning at 16.08.04 14:40:01 GMT. ALERT status is 8. Precipitation expected by 1440 GMT.
GANDOLF warning at 16.08.04 14:45:02 GMT. ALERT status is 8. Precipitation expected by 1445 GMT.
GANDOLF warning at 16.08.04 14:50:02 GMT. ALERT status is 8. Precipitation expected by 1450 GMT.
GANDOLF warning at 16.08.04 14:55:03 GMT. ALERT status is 8. Precipitation expected by 1455 GMT.
GANDOLF warning at 16.08.04 15:00:03 GMT. ALERT status is 8. Precipitation expected by 1500 GMT.
GANDOLF warning at 16.08.04 15:05:02 GMT. ALERT status is 8. Precipitation expected by 1505 GMT.
GANDOLF warning at 16.08.04 15:10:02 GMT. ALERT status is 8. Precipitation expected by 1510 GMT.
GANDOLF warning at 16.08.04 15:15:02 GMT. ALERT status is 8. Precipitation expected by 1515 GMT.
GANDOLF warning at 16.08.04 15:20:03 GMT. ALERT status is 8. Precipitation expected by 1520 GMT.
GANDOLF warning at 16.08.04 15:25:01 GMT. ALERT status is 8. Precipitation expected by 1525 GMT.
GANDOLF warning at 16.08.04 15:30:03 GMT. ALERT status is 8. Precipitation expected by 1530 GMT.
GANDOLF warning at 16.08.04 15:35:03 GMT. ALERT status is 8. Precipitation expected by 1535 GMT.
GANDOLF warning at 16.08.04 15:40:03 GMT. ALERT status is 8. Precipitation expected by 1540 GMT.
GANDOLF warning at 16.08.04 15:45:02 GMT. ALERT status is 8. Precipitation expected by 1545 GMT.
GANDOLF warning at 16.08.04 15:50:02 GMT. ALERT status is 9. Precipitation expected by 1550 GMT.
GANDOLF warning at 16.08.04 15:55:02 GMT. ALERT status is 9. Precipitation expected by 1555 GMT.
GANDOLF warning at 16.08.04 16:00:05 GMT. ALERT status is 9. Precipitation expected by 1600 GMT.
GANDOLF warning at 16.08.04 16:05:02 GMT. ALERT status is 9. Precipitation expected by 1605 GMT.
GANDOLF warning at 16.08.04 16:10:02 GMT. ALERT status is 9. Precipitation expected by 1610 GMT.
GANDOLF warning at 16.08.04 16:15:02 GMT. ALERT status is 9. Precipitation expected by 1615 GMT.
GANDOLF warning at 16.08.04 16:20:01 GMT. ALERT status is 9. Precipitation expected by 1620 GMT.
GANDOLF warning at 16.08.04 16:25:02 GMT. ALERT status is 9. Precipitation expected by 1625 GMT.
GANDOLF warning at 16.08.04 16:30:03 GMT. ALERT status is 7. Precipitation expected by 1630 GMT.
GANDOLF warning at 16.08.04 16:35:02 GMT. ALERT status is 8. Precipitation expected by 1635 GMT.
GANDOLF warning at 16.08.04 16:40:02 GMT. ALERT status is 8. Precipitation expected by 1640 GMT.
GANDOLF warning at 16.08.04 16:45:01 GMT. ALERT status is 8. Precipitation expected by 1645 GMT.
GANDOLF warning at 16.08.04 16:50:01 GMT. ALERT status is 9. Precipitation expected by 1650 GMT.
GANDOLF warning at 16.08.04 16:55:02 GMT. ALERT status is 9. Precipitation expected by 1655 GMT.
GANDOLF warning at 16.08.04 17:00:03 GMT. ALERT status is 9. Precipitation expected by 1700 GMT.
GANDOLF warning at 16.08.04 17:05:02 GMT. ALERT status is 9. Precipitation expected by 1705 GMT.
GANDOLF warning at 16.08.04 17:10:02 GMT. ALERT status is X.
GANDOLF warning at 16.08.04 17:15:02 GMT. ALERT status is X.
GANDOLF warning at 16.08.04 17:20:02 GMT. ALERT status is X.
GANDOLF warning at 16.08.04 17:25:03 GMT. ALERT status is 9. Precipitation expected by 1725 GMT.
GANDOLF warning at 16.08.04 17:30:03 GMT. ALERT status is 9. Precipitation expected by 1730 GMT.
GANDOLF warning at 16.08.04 17:35:02 GMT. ALERT status is 8. Precipitation expected by 1735 GMT.
GANDOLF warning at 16.08.04 17:40:03 GMT. ALERT status is 8. Precipitation expected by 1740 GMT.
GANDOLF warning at 16.08.04 17:45:03 GMT. ALERT status is 8. Precipitation expected by 1745 GMT.
GANDOLF warning at 16.08.04 17:50:01 GMT. ALERT status is 8. Precipitation expected by 1750 GMT.
GANDOLF warning at 16.08.04 17:55:02 GMT. ALERT status is 8. Precipitation expected by 1755 GMT.
GANDOLF warning at 16.08.04 18:00:04 GMT. ALERT status is 8. Precipitation expected by 1800 GMT.
GANDOLF warning at 16.08.04 18:05:02 GMT. ALERT status is 8. Precipitation expected by 1805 GMT.
GANDOLF warning at 16.08.04 18:10:01 GMT. ALERT status is 8. Precipitation expected by 1810 GMT.
GANDOLF warning at 16.08.04 18:15:01 GMT. ALERT status is 8. Precipitation expected by 1815 GMT.
GANDOLF warning at 16.08.04 18:20:01 GMT. ALERT status is 8. Precipitation expected by 1820 GMT.
GANDOLF warning at 16.08.04 18:25:04 GMT. ALERT status is 8. Precipitation expected by 1825 GMT.
GANDOLF warning at 16.08.04 18:30:02 GMT. ALERT status is 8. Precipitation expected by 1830 GMT.
GANDOLF warning at 16.08.04 18:35:02 GMT. ALERT status is 8. Precipitation expected by 1835 GMT.
GANDOLF warning at 16.08.04 18:40:02 GMT. ALERT status is 8. Precipitation expected by 1840 GMT.
GANDOLF warning at 16.08.04 18:45:02 GMT. ALERT status is 8. Precipitation expected by 1845 GMT.
GANDOLF warning at 16.08.04 18:50:01 GMT. ALERT status is 7. Precipitation expected by 1850 GMT.
GANDOLF warning at 16.08.04 18:55:01 GMT. ALERT status is 7. Precipitation expected by 1855 GMT.
GANDOLF warning at 16.08.04 19:00:03 GMT. ALERT status is 7. Precipitation expected by 1900 GMT.
GANDOLF warning at 16.08.04 19:05:02 GMT. ALERT status is 7. Precipitation expected by 1905 GMT.
```

Figure 5a Excerpt from Gandolf heavy rainfall warning messages log for south-west England.

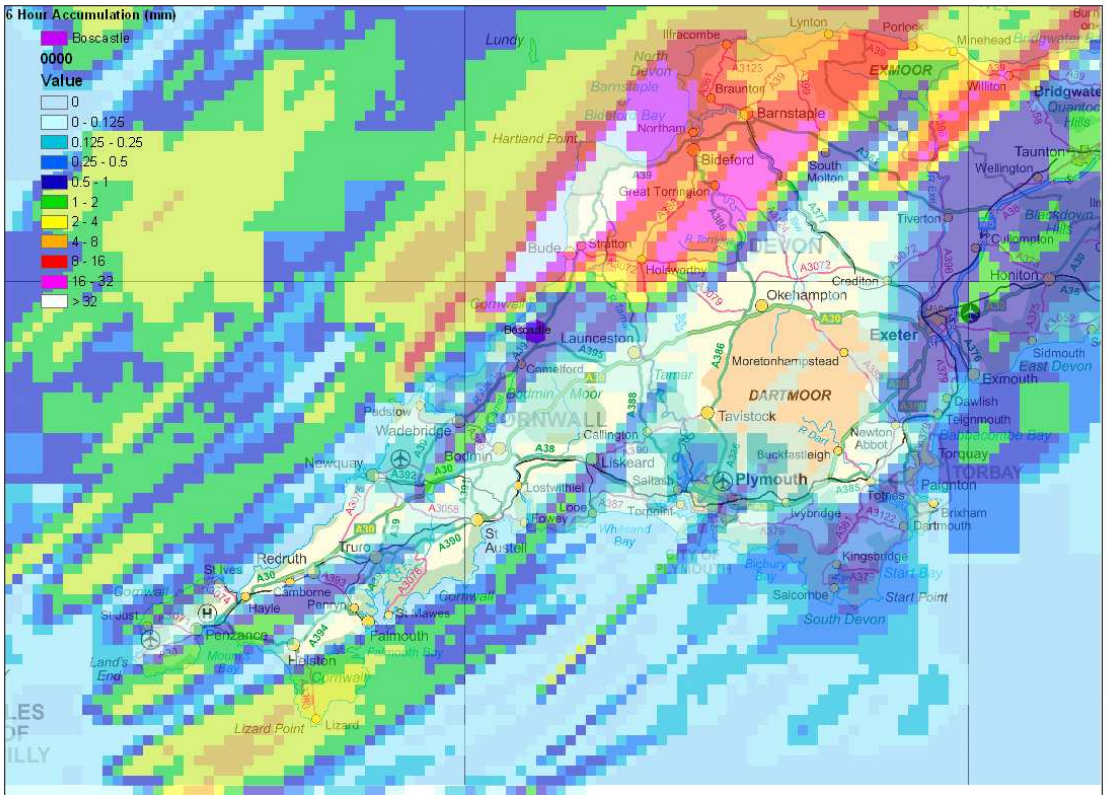



Figure 5b A six hour accumulation estimated from the Gandolf forecast valid for the period 1615 UTC to 2215 UTC on 16 August 2004. Gandolf heavy rainfall warnings issued from 1550 UTC onwards and predicting hourly accumulations in excess of 32 mm were triggered by the heavy rain advected down wind of Boscastle.

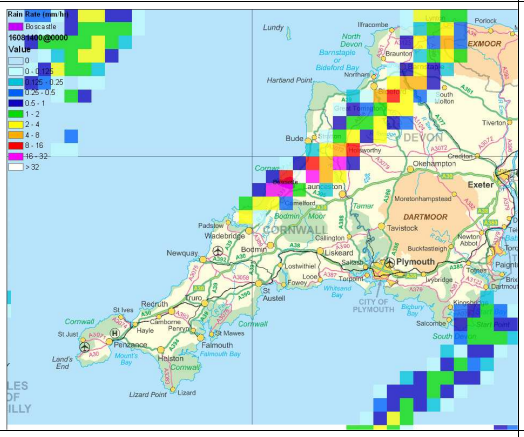
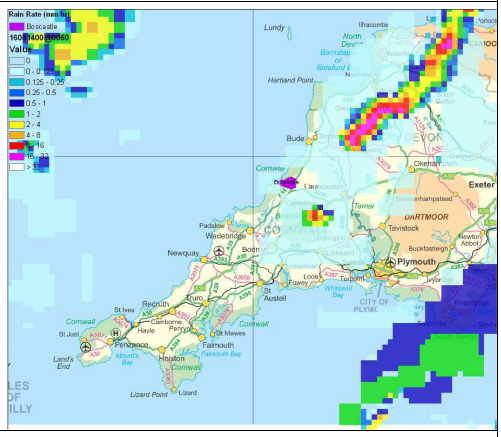
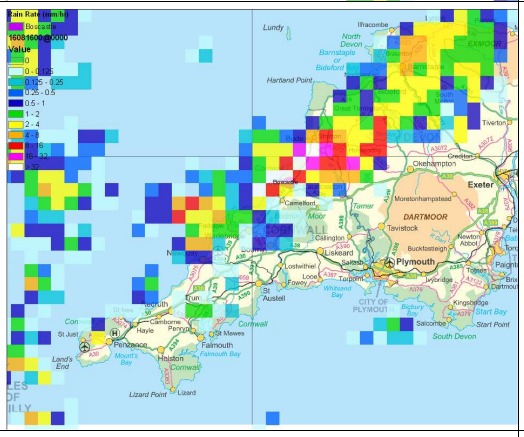
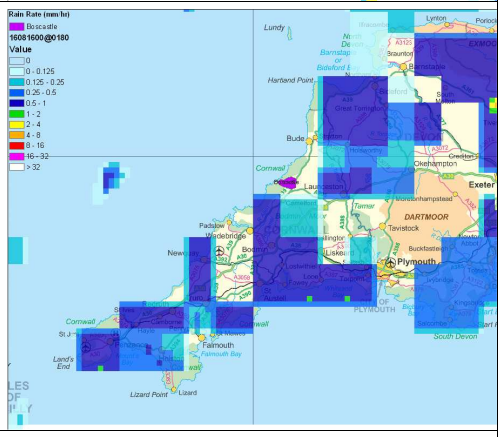
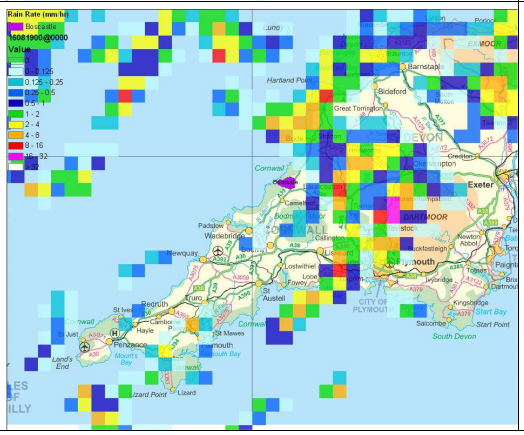
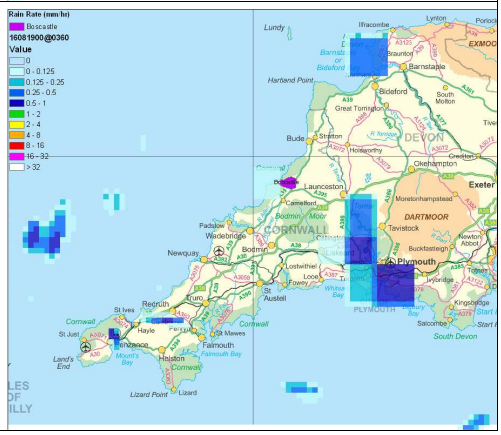
| Validity time / Forecast lead time | Radar composites of instantaneous rain rate | Gandolf nowcasts of instantaneous rain rate for a single run valid at 1300 UTC, 16 August 2004 |
|---|---|---|
| 1400 UTC / T+1 h |  |  |
| 1600 UTC / T+3 h |  |  |
| 1900 UTC / T+6 h |  |  |

**Figure 6 A comparison of Gandolf T+1h, T+3h and T+6h nowcasts of rain rate with time synchronous radar composite analyses of rain rate valid at 1400 UTC, 16 August 2004 and 1900 UTC respectively on 16 August 2004.**

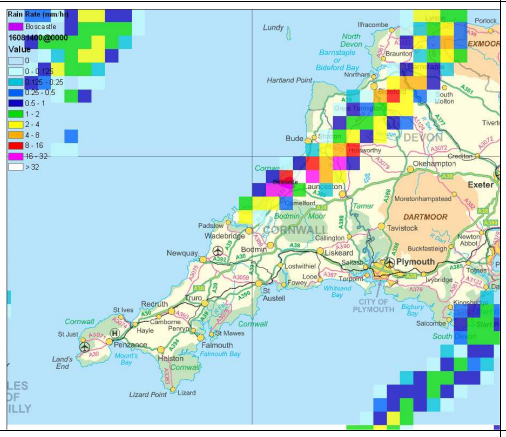
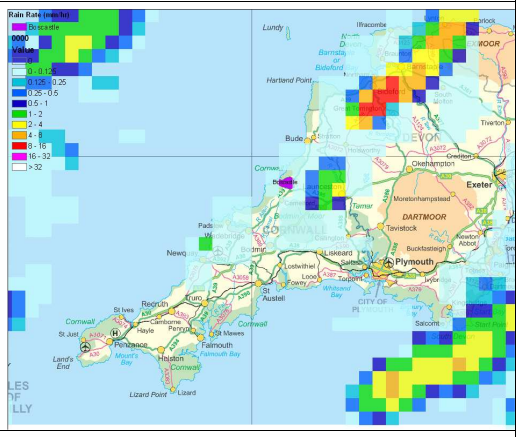
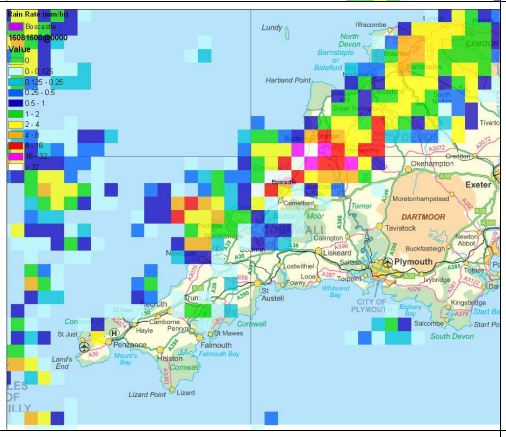
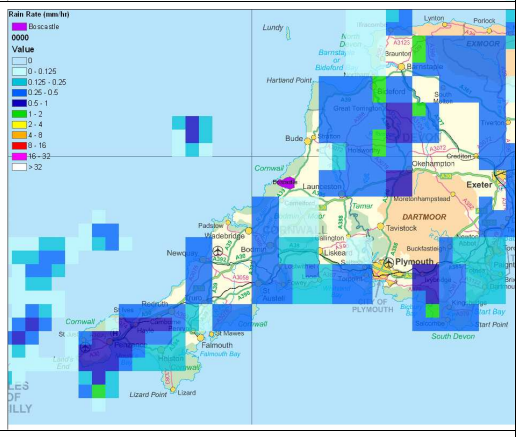
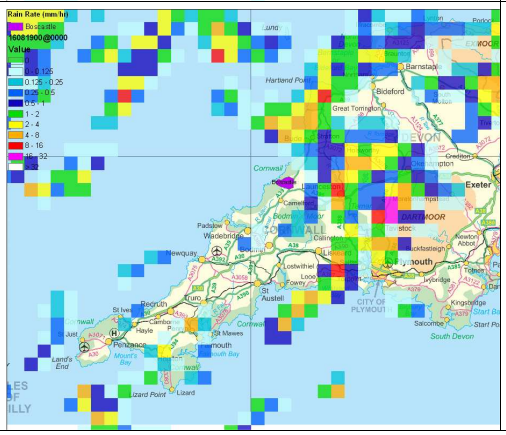
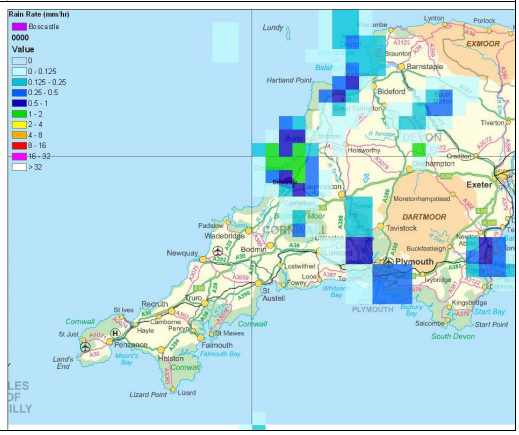
| Validity time / Forecast lead time | Radar composites of instantaneous rain rate | Nimrod forecasts of instantaneous rain rate for a single run valid at 1300 UTC, 16 August 2004 |
|---|---|---|
| 1400 UTC / T+1 h |  |  |
| 1600 UTC / T+3 h |  |  |
| 1900 UTC / T+6 h |  |  |

**Figure 7 A comparison of Nimrod T+1 h, T+3h and T+6h nowcasts of rain rate with time synchronous radar composite analyses of rain rate valid at 1400 UTC, 1600 UTC and 1900 UTC respectively on 16 August 2004.**

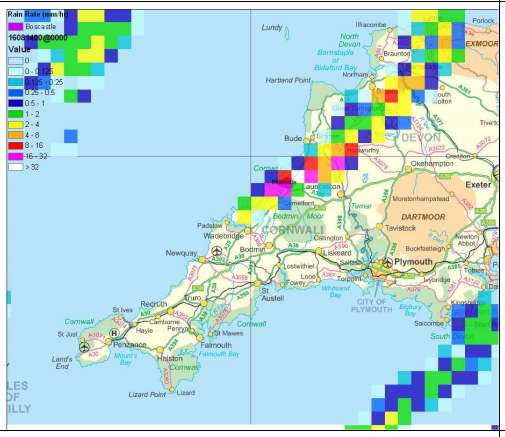
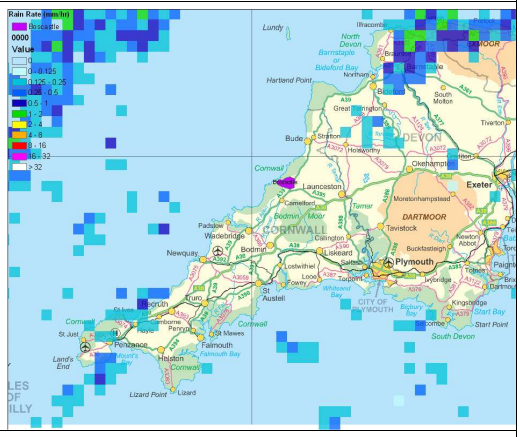
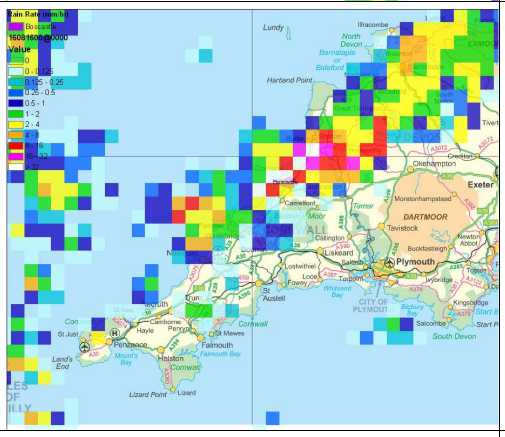
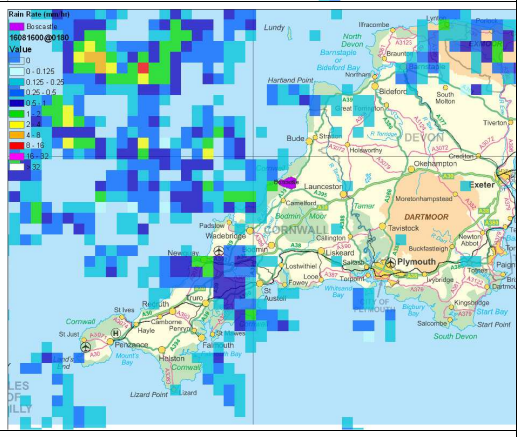
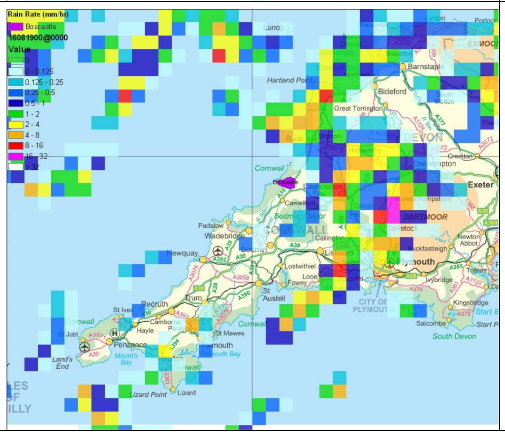
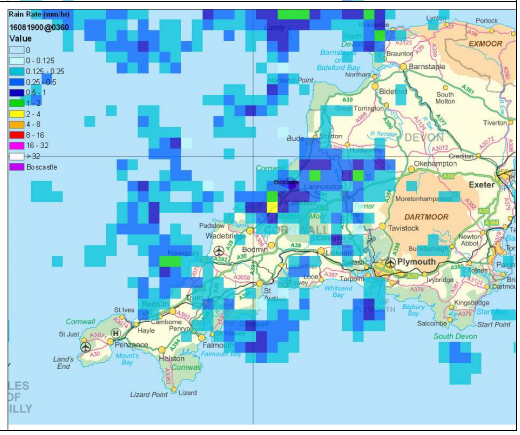
| Validity time / Forecast lead time | Radar composites of instantaneous rain rate | STEPS forecasts of instantaneous rain rate for a single run valid at 1300 UTC, 16 August 2004, ensemble member 14 |
|---|---|---|
| 1400 UTC / T+1 h |  |  |
| 1600 UTC / T+3 h |  |  |
| 1900 UTC / T+6 h |  |  |

**Figure 8 A comparison of STEPS T+1 h, T+3h and T+6h nowcasts of rain rate with time synchronous radar composite analyses of rain rate valid at 1400 UTC, 1600 UTC and 1900 UTC respectively on 16 August 2004. Ensemble member 14 is shown.**

## 2.6 Performance of the operational Convection Diagnosis Procedure (CDP)

Although not strictly a Nowcasting system the Met Office Convection Diagnosis Procedure (CDP) provides probabilistic guidance on expected convective activity forced locally from surface conditions. The CDP is run 4 times a day from data at 00, 06, 12, 18 producing forecasts from T+6 to T+36 hours ahead. The CDP post-processes Mesoscale model data and has a simple life-cycle model of convection. The model is able to trigger showers and then advect them with appropriate winds as they go through their various stages of development, full maturity and decay. The DT 0600 run on the 16 August was available at 0935 UTC. Figure 9 shows the forecast probability of getting showers in SW England and figure 10 shows the expected peak rainfall rate. In figure 9, at and above the 50% probability level, the CDP was expecting showers to be organised into lines moving northeast. The charts can be interpreted as showing showers subsequently decaying with more showers forming upwind. The shower line was not quite in the correct place but gave useful guidance as to the likely organisation of the convection. The primary mechanism for triggering in the CDP on this occasion was insolation and elevated heating using its 1 Km scale representation of orography. However, showers were not confidently triggered over all high ground in the SW, and it appears that the CDP was able to make use of information in the Mesoscale model that would correctly suggest that showers were less likely over Dartmoor, for example.

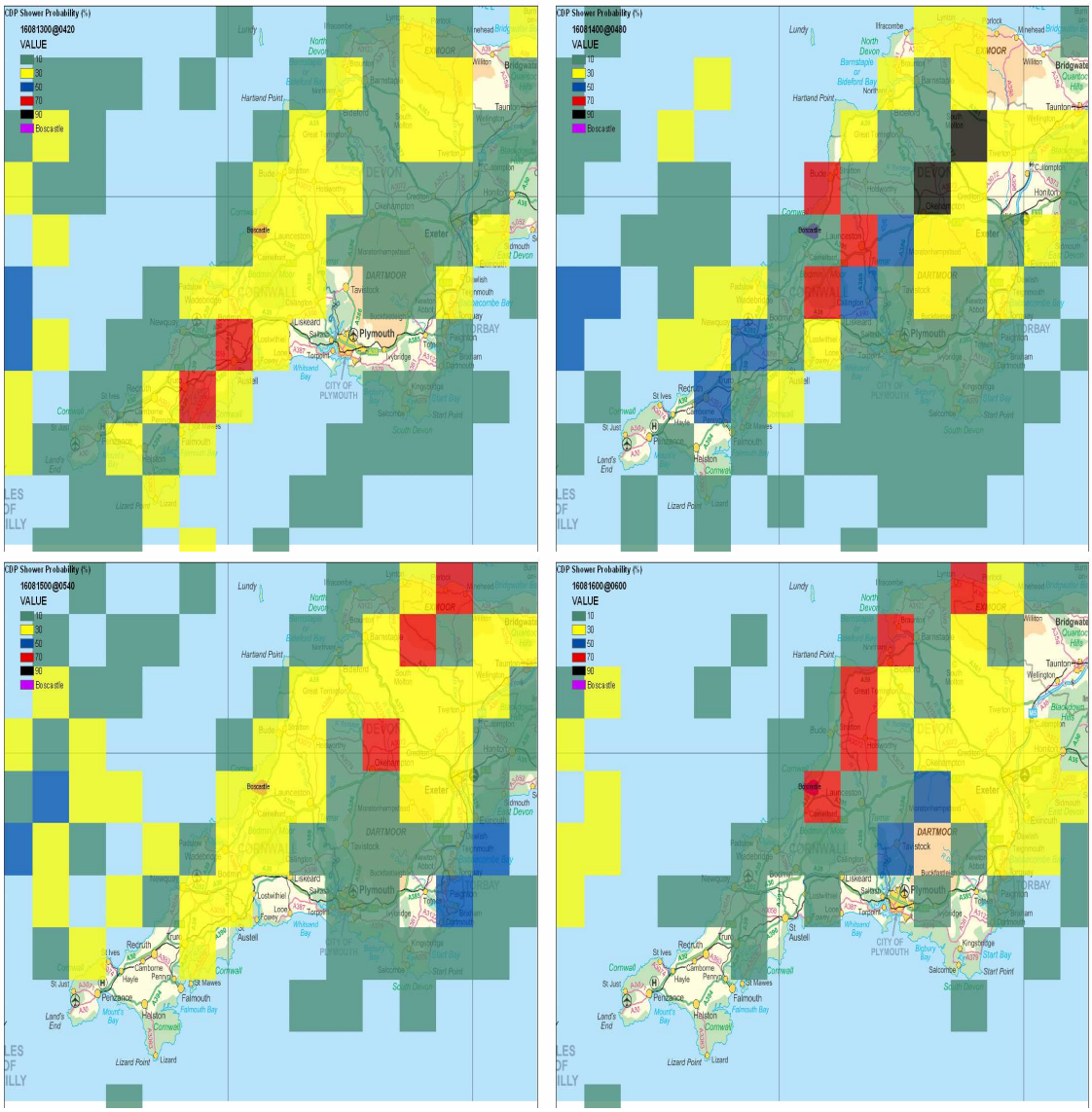



**Figure 9 CDP forecast probabilities of getting showers in Nimrod 15 Km pixels at 1300, 1400, 1500 and 1600 UTC 16 August 2004 from DT 0600 UTC 16 August 2004.**

The peak rainfall rates from the CDP shown in figure 10 were mostly in the range 8-32 mm/h with only isolated pixels with rates > 32 mm/h . These are not exceptional and this range of rates would be seen in many other CDP forecasts. The peak rainfall rate in the CDP depends on the mean rate diagnosed using the UM convection scheme and the expected base area of the convective cells as they progress through their life-cycles.

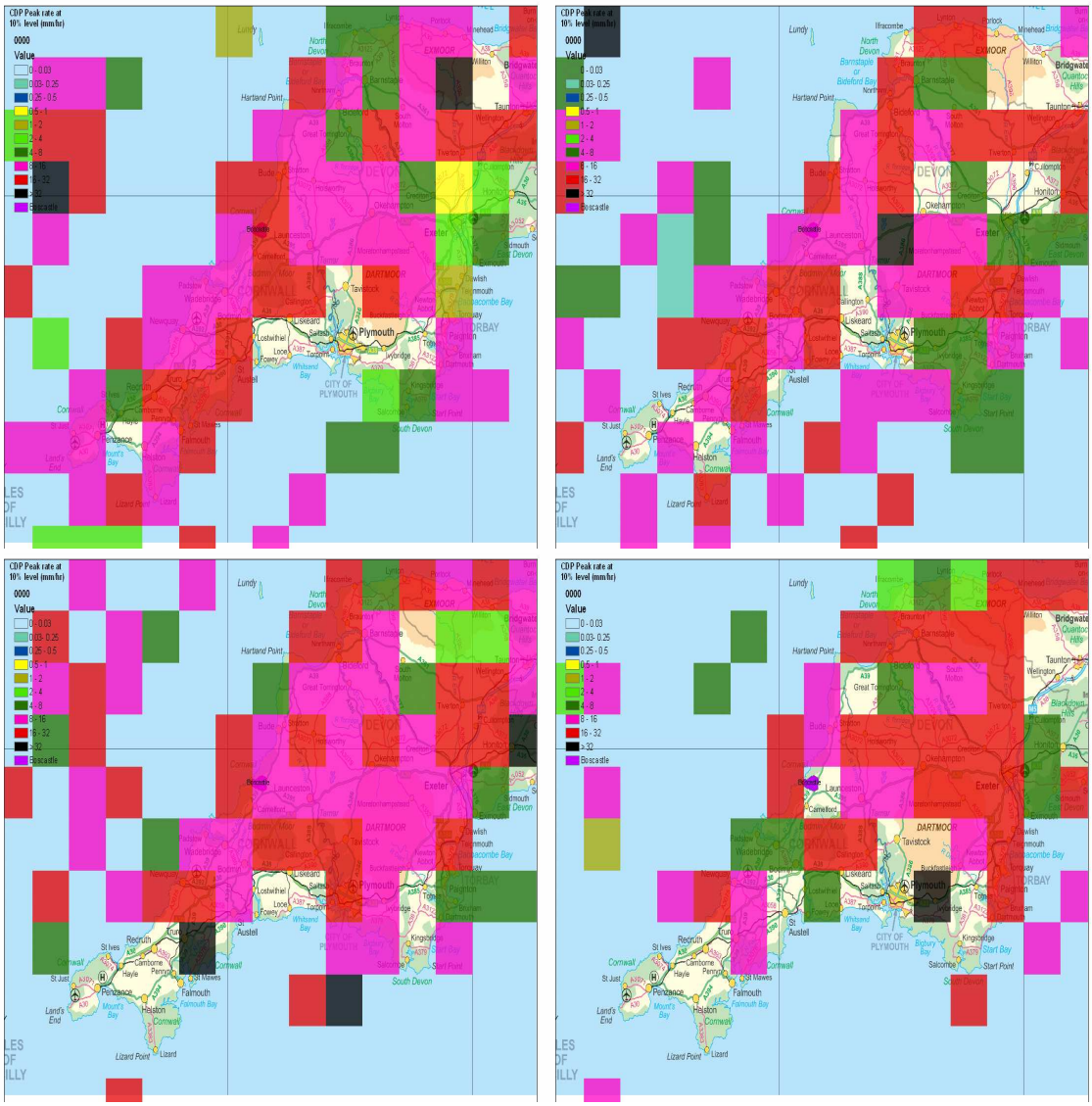


**Figure 10 Peak rainfall rates from CDP shower forecast at 1300, 1400, 1500 and 1600 UTC 16 August 2004 from DT 0600 UTC 16 August 2004.**

## 2.7 Review of predicted accumulations in the Valency river catchment

Figure 11 compares catchment average accumulations predicted by Nimrod, Gandolf and STEPS (ensemble mean) with those estimated from 2 km Cobbacombe weather radar for three separate 6 hour integration periods commencing at 1100 UTC, 1300 UTC and 1500 UTC respectively on 16 August 2004. In all cases the forecast accumulations fall a long way short of those estimated from radar observations for reasons explained earlier.

Figure 12 shows STEPS' Probability Density Functions (pdfs) of 6 hour accumulations for the Valency catchment from three separate model runs valid - 1100 UTC, 1300 UTC and 1500 UTC. All three runs substantially under predict the accumulation estimated from weather radar. The failure to capture the severity of the event within the ensemble spread is largely due to the failure of the MM to predict convective precipitation over the Valency catchment.

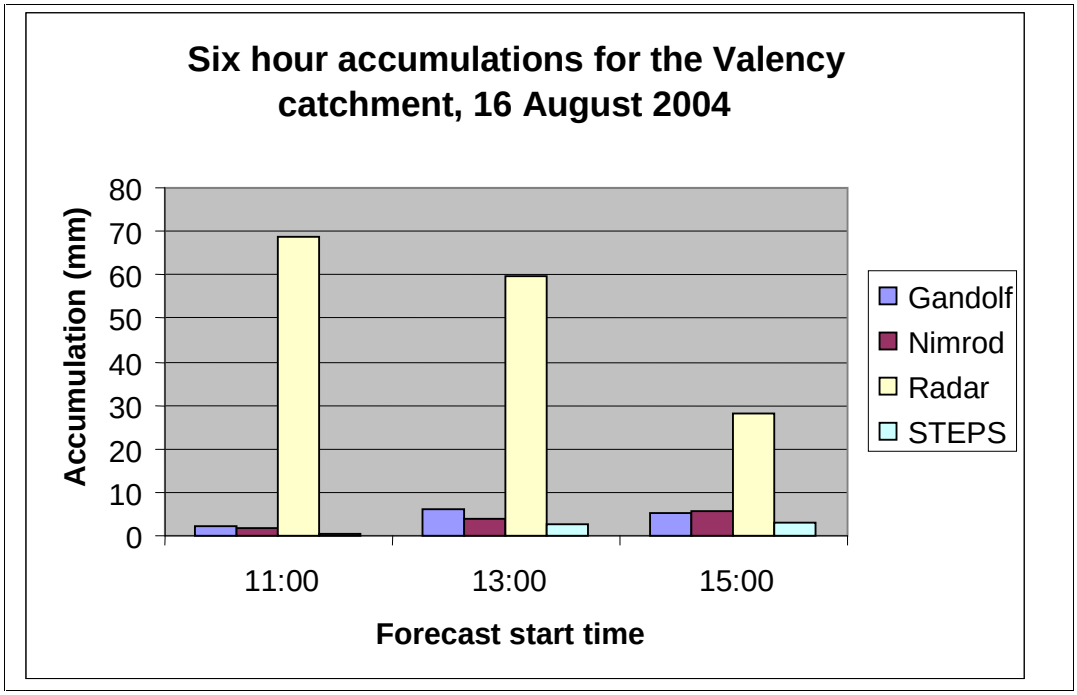



Figure 11 Six hour accumulations for the Valency catchment on 16 August 2004. Radar accumulations (2 km Cobbacombe Cross- yellow) are compared with Gandolf (blue) and Nimrod (red) forecast accumulations, and a 50 member ensemble mean accumulation from STEPS.

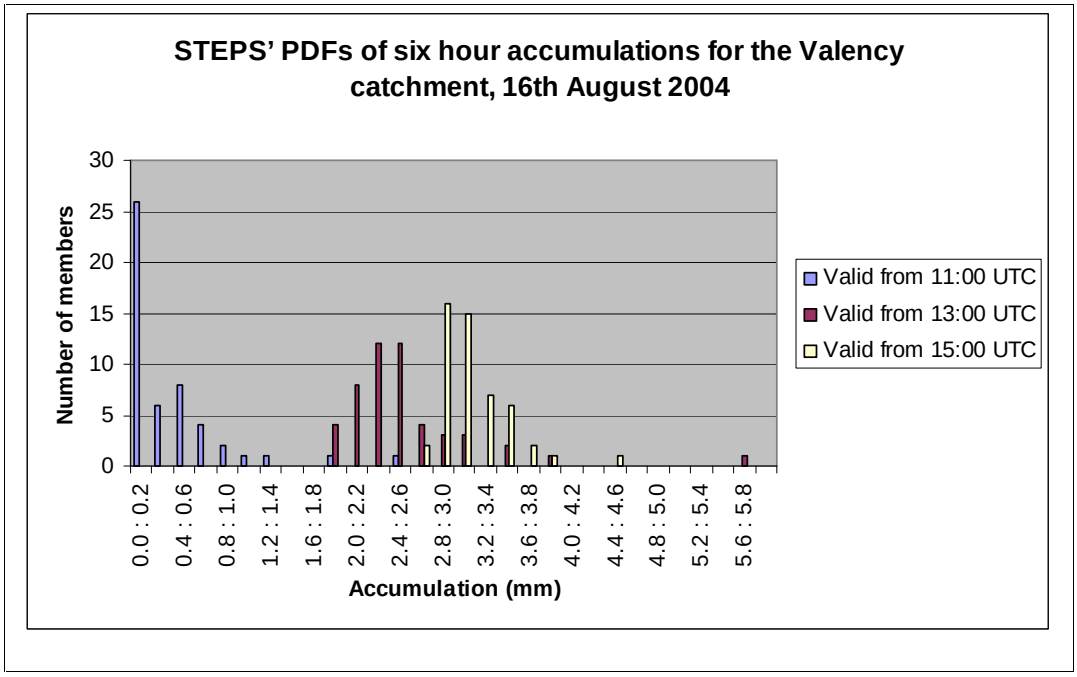



Figure 12 STEPS' pdfs of six hour accumulation for the Valency catchment on 16 August 2004. Three runs with Data Times of 1100 UTC, 1300 UTC and 1500 UTC are shown. Member 14 of the 1300 UTC run produced the highest accumulation of a little under 6 mm.

## 3.0 Mesoscale NWP Performance

### 3.1 Introduction

This section summarises results from a run of the High Resolution Trial Model suite (HRTM) at 4 km and 1 km resolution and compares with the operational 12 km model. This high resolution NWP is not currently available operationally.

### 3.2 Forecast Run

The HRTM has been set up primarily to provide research results which may be compared with data from the Chilbolton research radar in Hampshire. It comprises a 4 km and a 1 km domain centred on Chilbolton. The 4 km model is embedded in the operational 12 km model and the 1 km embedded in the 4 km. The HRTM domains are shown below. The 1 km domain was not appropriate for Boscastle, so was not run, and a new 1 km domain was set up specifically for this study post-event.

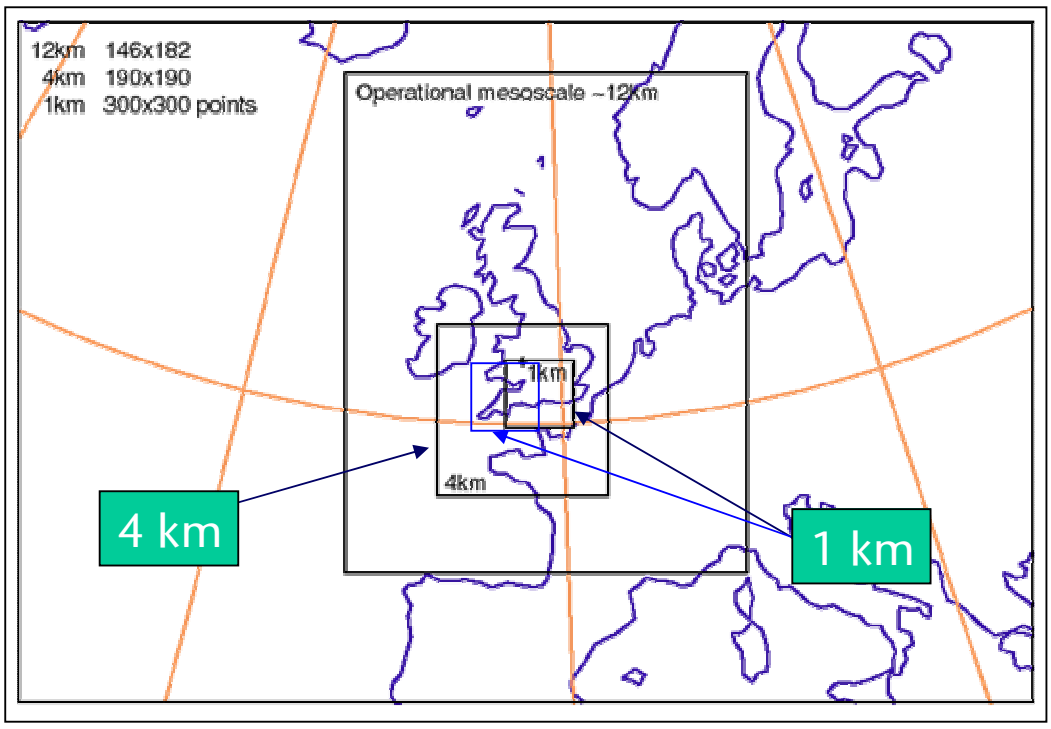



**Figure 13 HRTM domains. Boscastle 1 km domain shown in blue.**

The suite has been run with a 3DVAR data assimilation cycle in the 4 km domain; however, this requires continuous running and is not yet optimized. The results described here therefore use the 12 km model state. The 12 km model at T+1, i.e. one hour into the forecast, is used as this represents the state after 3D VAR increments have been 'nudged' in via the IAU and MOPS and Latent Heat Nudging are almost complete.

Runs were started using the 0000 and 0300 UTC 12km analysis (i.e. at 0100 and 0400). The run started from the 0300 UTC 12 km model analysis provides most of the results below;

this would have been available prior to the event and so is relevant in a nowcasting context. In practice, forecasts from the 12 km model are not produced at this (intermediate) time, but the performance is likely to be similar to the 0000 UTC run. The intention here is to highlight the potential of the 4 km model in a nowcasting framework.

## 3.3 Forecast rainfall accumulations

The 12 and 4 km model accumulation from the 0300UTC runs are compared in Fig. 14. 12-km grid length model produced fairly uniform (and not insignificant) accumulations but failed to predict a localised event. The 4-km grid length HRTM forecast was much better. It produced a line of storms close to the correct location and rainfall accumulations of over 70mm in a few hours. The pictures below show that the 4-km forecast was considerably better than the 12-km forecast in predicting high rainfall accumulations in the right region (but not exactly the right place).

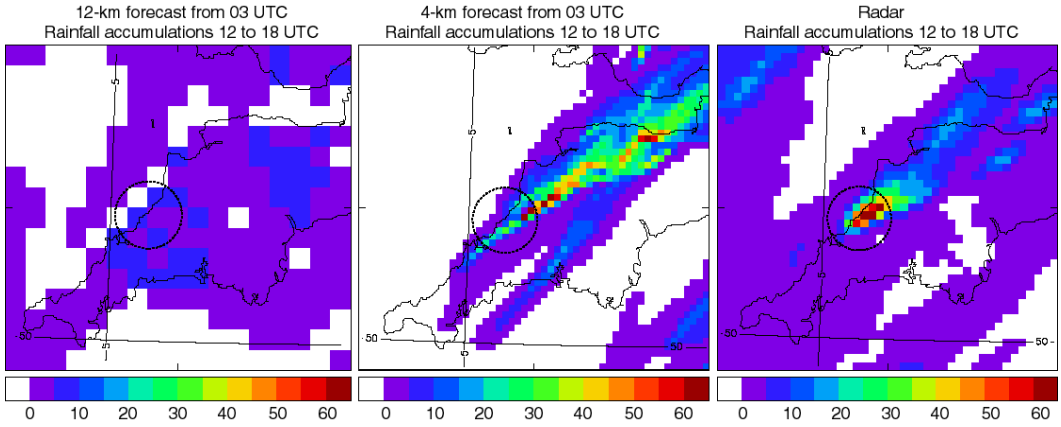



**Figure 14 Rainfall accumulations from 1200-1800 UTC on 16 August 2004. 12 km model from 0300 UTC (left), 4 km model from 0300 UTC (centre) and NIMROD radar accumulations (right). The circle is a 20 km radius from Boscastle.**

4 km and 1 km forecasts were only run to T+15 because of cost. The 0000 UTC run therefore only extended to 1500 UTC and did not cover the whole event. Figure 15 shows the accumulation from 1200-1500 UTC from the 0300 UTC run compared with the same from the 0000 UTC run. The 1200-1800 accumulation from the 0300 UTC run and the same from the subsequently run 1 km are shown for comparison.

Several points may be noted:

1.) The 0000 UTC 4 km forecast is remarkably good, though the highest accumulations fall over the sea.
2.) The 0000 UTC forecasts appear to be better than the later 0300 UTC forecast.
3.) Both show the swath of rainfall originating from roughly the same place.
4.) Most of the accumulation over Boscastle in the 0300 UTC run fell between 1200 and 1500 UTC. The accumulations to the northeast fell later.
5.) The 1 km forecast shows a better location than the 4 km forecast but lower (though still high) accumulations. In other cases, we have found that the 4 km run tends to over-predict, as a result of under-resolution of convective cells. We would normally regard the 1 km model as more reliable, though we would emphasise again that only a limited amount of experience has been gained.
6.) Given the differences noted above, the similarities between runs are remarkable and provide some confidence in the predictability of the event.

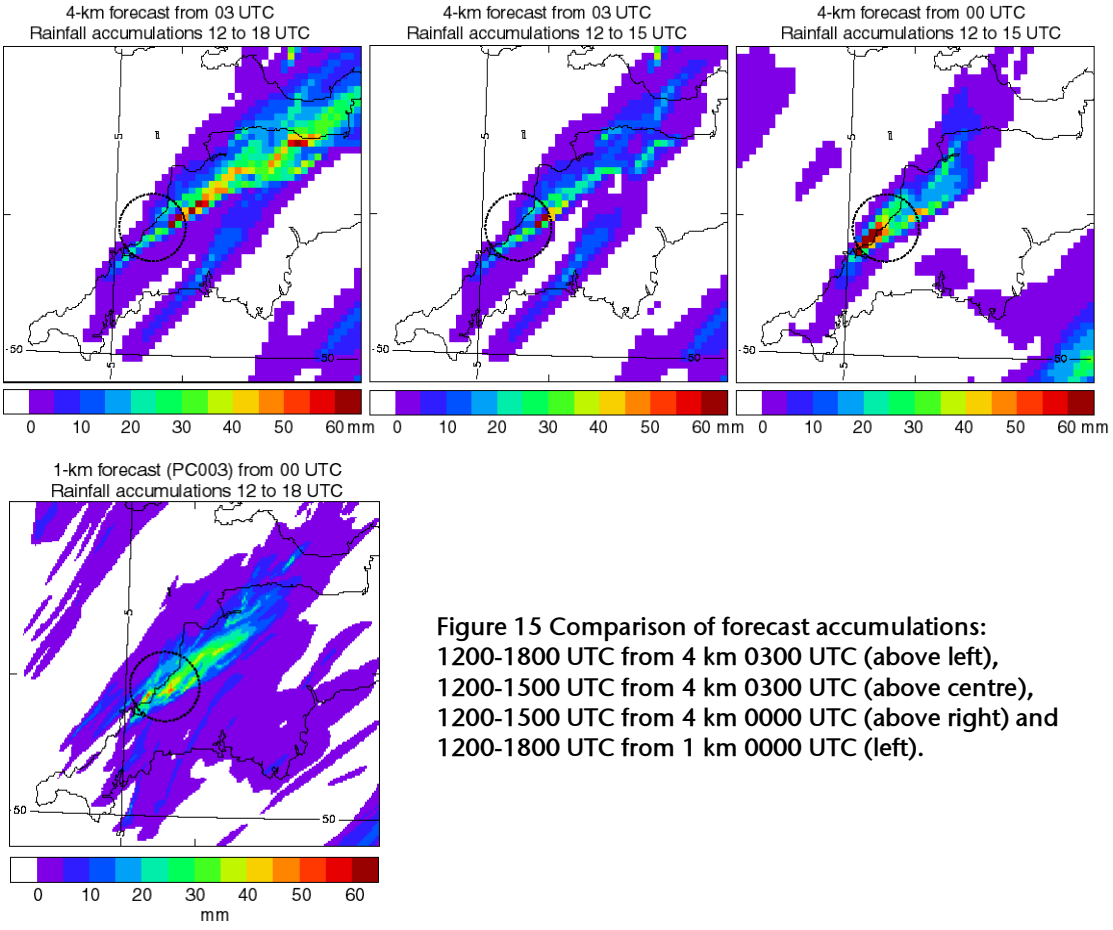



**Figure 15 Comparison of forecast accumulations: 1200-1800 UTC from 4 km 0300 UTC (above left), 1200-1500 UTC from 4 km 0300 UTC (above centre), 1200-1500 UTC from 4 km 0000 UTC (above right) and 1200-1800 UTC from 1 km 0000 UTC (left).**

In practice, a 4 km model is more practicable than a 1 km model, so we shall emphasise further analysis on this resolution. Results at 4 km are very encouraging, **but** it should be remembered that this is a system which is very much under development – it is difficult to know how much reliance can be put on a single forecast. Even in this case the predicted rainfall did not fall into exactly the right river catchment and the later forecast also produced high totals in other areas that were not flooded. The problem here is in the **interpretation** of a 4-km grid length model. We should not expect a 4-km model to be consistently accurate to within a few grid lengths (~20 km) or, perhaps, even considerably more. We need to post-process high-resolution-model rainfall to produce useful products.

The way to make the best use out of a high-resolution forecast system is to produce appropriate precipitation output diagnostics on scales which can be relied upon. This will almost certainly mean degrading the apparent resolution of the forecast in various ways. This will enable us to extract the information we want without having unrealistic expectations of a models capability. We need to use the model to get, for example, an assessment of the risk of a rainfall accumulation being exceeded within a susceptible river catchment or the highest accumulation that could occur within a particular region or the highest rainfall rate that might occur on a say a stretch of motorway. All this needs to take into account that the model forecast will be in error to some extent but will also contain a great deal of useful information.

## 3.4 Post-processed output from the 4-km gridlength simulation of the Boscastle flood

### 3.4.1 Mean and Total accumulations over river catchments

We have used large scale Environment Agency 'catchments' as shown above to aggregate rainfall in a more meaningful way. These generally identify major river catchments, but the area containing Boscastle is very diffuse, containing numerous small rivers.

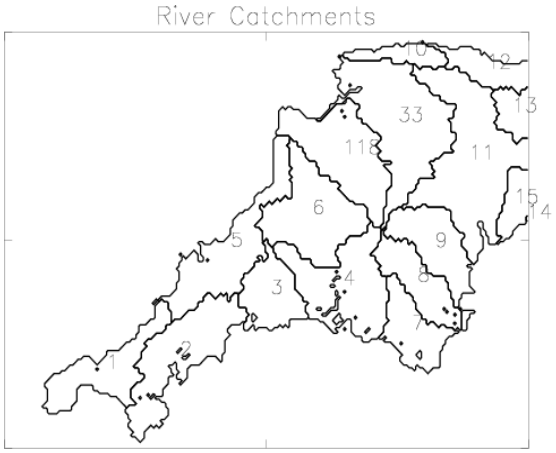



**Figure 16 Environment Agency catchment boundaries. Note, the catchment containing Boscastle contains several rivers.**

Figure 17 shows the average rainfall accumulations over river catchments for the period 1200 to 1500 UTC from the 0000 UTC 4 km run and from 1200 to 1800 UTC from the 0300 UTC 4 km run. The river catchments are displayed on the 4-km model grid after being averaged to that grid from the original 1-km resolution catchment map (so have degraded resolution from the original catchment dataset). It is clear that the catchment average rainfall accumulations shown here are not particularly dramatic. ~10-18 mm in the Boscastle area. This is a result of choosing to display large catchment areas that did not have much forecast rain over the larger part of their area. It is also evident that the most threatened regions in the later run are in north Devon and Somerset rather than in the Boscastle area. Catchment totals for 1200-1800 UTC on 16 August 2004 are shown in Table 2 ($x10^6$kg):

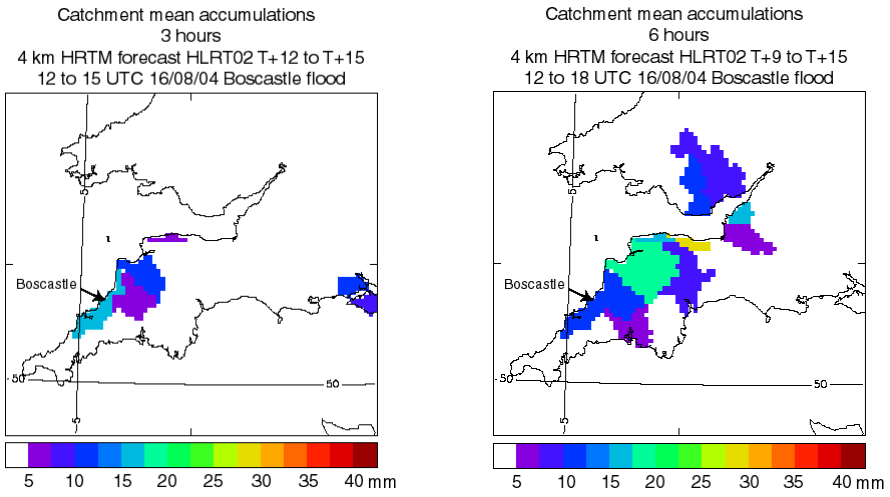



**Figure 17 Forecast Environment Agency catchment totals: 1200-1500 UTC from 0000 UTC (left) and 1200-1800 UTC from 0300 UTC (right).**

**Table 2 Catchment totals 12-18 UTC on 16 August 2004**

| ID | 12km | 4km | Radar | Name (size) |
|---|---|---|---|---|
| 5 | 4174 | 8230 | 12066 | Camel and North Coast Streams (856 sq. km) |
| 6 | 3870 | 10997 | 11680 | Tamar and Tributaries (912 sq. km) |
| 118 | 2644 | 16839 | 9899 | Brue (789 sq. km) |
| 33 | 5289 | 23170 | 7727 | West Dorset Streams (523 sq. km) |
| 11 | 8003 | 12166 | 4814 | Exe (1509 sq. km) |
| 10 | 482 | 2957 | 2345 | North Devon Streams (205 sq. km) |
| 2 | 2982 | 880 | 1508 | Fal & St Austell Rivers (879 sq. km) |
| 13 | 970 | 1902 | 1506 | Tone and Parrett (1696 sq. km) |
| 12 | 1028 | 8601 | 1482 | West Somerset Streams (314 sq. km) |
| 1 | 1645 | 117 | 1338 | Hayle and Red Rivers (598 sq. km) |
| 4 | 4076 | 4580 | 672 | Tamar Estuary and Tributaries (902 sq. km) |
| 3 | 2505 | 553 | 550 | Seaton/Looe/Fowey (475 sq. km) |
| 15 | 933 | 2 | 279 | Sid and Otter (295 sq. km) |
| 7 | 1771 | 53 | 231 | Avon and Erme (454 sq. km) |
| 8 | 1483 | 496 | 180 | Dart (473 sq. km) |
| 9 | 1721 | 802 | 113 | Teign (586 sq. km) |
| 14 | 4 | 0 | 2 | Lim and Axe (458 sq. km) |
| Total | 58182 | 110430 | 85710 | |

The catchments are ordered in descending radar-derived total, with the Boscastle-containing catchment at the top. These are shown on a scatter diagram in Figure 18. This shows much better correlation between actual and forecast precipitation totals in the 4 km model compared with the 12 km model, but a general tendency to over-forecast in the4 km compared with the tendency of the 12 km model to under-forecast (in this event).

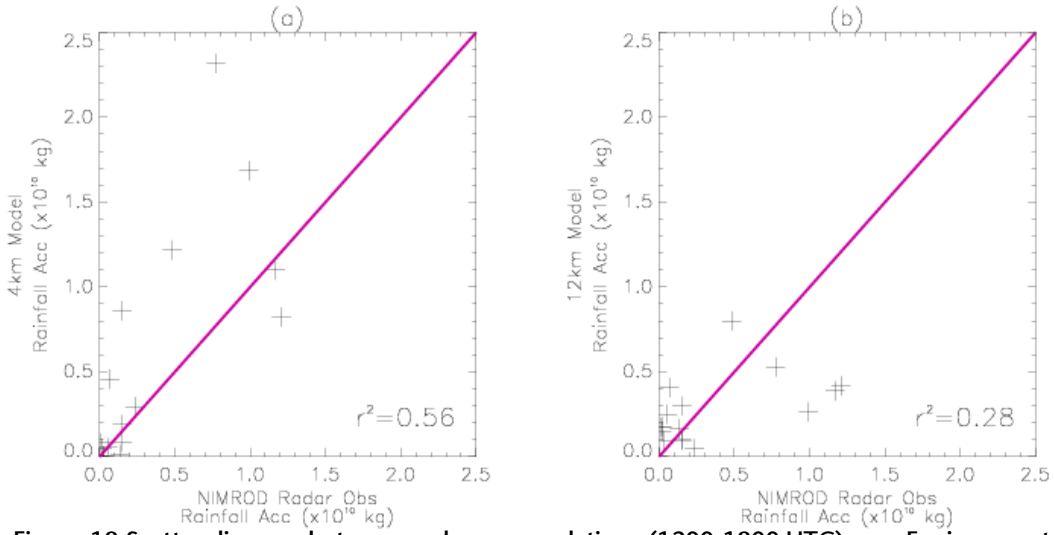



**Figure 18 Scatter diagram between radar accumulations (1200-1800 UTC) over Environment Agency catchments and 4 km (left) and 12 km (right) from 0300 UTC forecasts.**

### 3.4.2 Highest catchment accumulations, taking account of possible model error

Figure 19 illustrates a way of taking into account displacement errors in the 4-km forecast. We assume that any rain that fell in the forecast within a certain distance of the catchment could have fallen in the catchment. We have taken the distance as 20 km. We also acknowledge that these catchment areas do not represent individual areas 'at risk', so we consider the highest accumulation that could fall over a given fraction of the area of the catchment. The highest average accumulation is found by sorting the rainfall accumulations within the larger area (extended 20km beyond a catchment) so that the highest valued pixels within the larger area equal to the number of pixels in the (fractional) catchment itself are added together and divided by the number of pixels in the (fractional) catchment.

The aim is to see what a 'worst case' scenario might be if the model is wrong in rainfall location by up to 20 km. This is a sensible thing to do because we know that the model can often be wrong by that amount at least and that a small redistribution of the rain can have a large impact on the amount to fall into a river catchment on some occasions. The fractional catchment products highlight risk to small rivers and tributaries – in this case a number of catchments are shown at risk of greater than 50 mm accumulation in the 1/5 catchment product, including the Boscastle catchment in both forecasts. This product would be a useful product for all areas where there are small fast-response river catchments such as in Devon and Cornwall and in urban areas such as London. It reveals the risk to small regions, but displays the information over the larger geographically related catchments to show that there is uncertainty in the model forecasts.

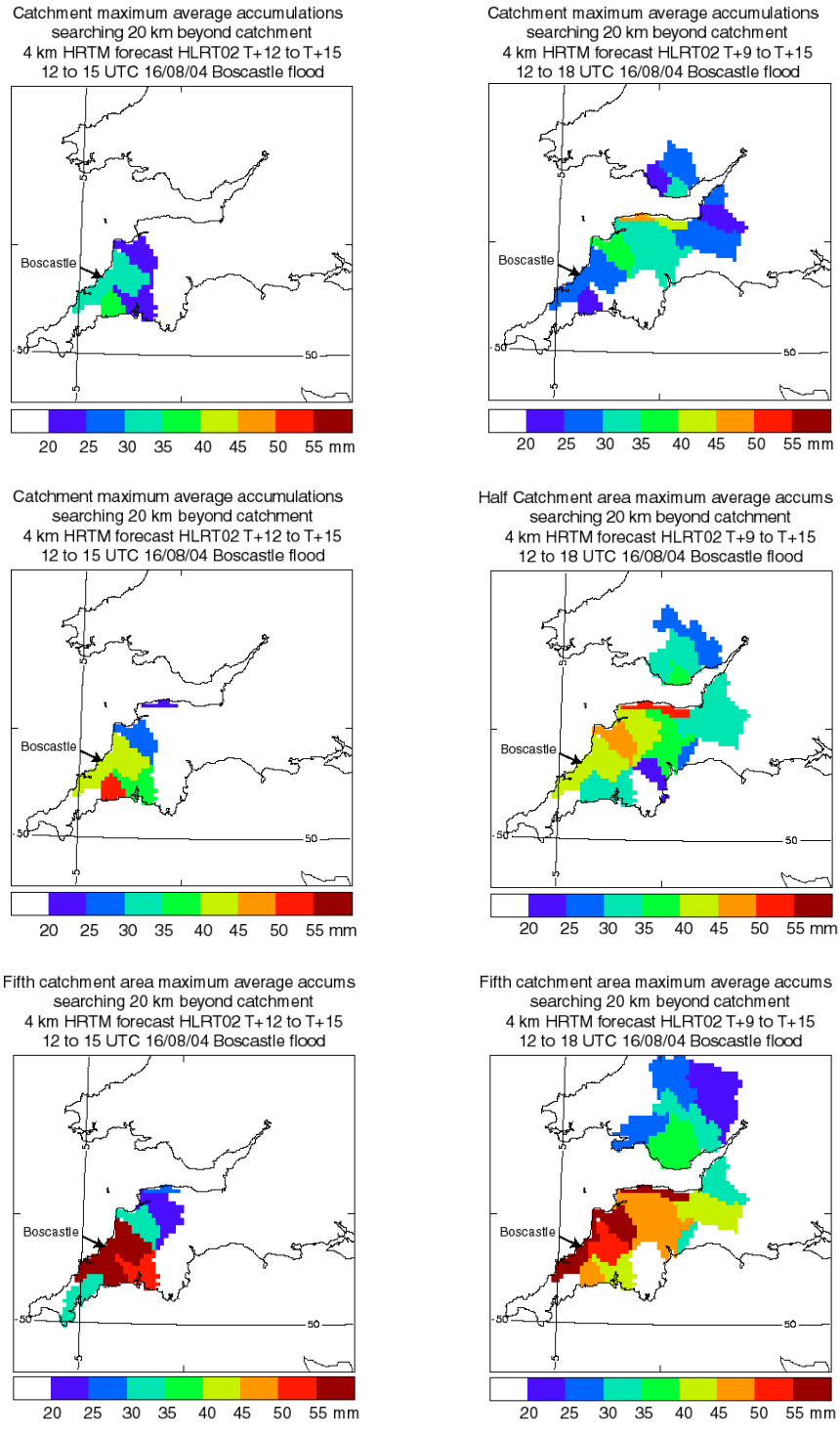



Figure 19 Estimates of catchment average accumulations taking account of possible model error of 20 km location. 0000 UTC run, 1200-1500 UTC accumulations (left), 0300 UTC run, 1200-1800 UTC accumulations (right). Highest accumulations over whole catchment area (top), half (middle) and one fifth (bottom).

### 3.4.3 The highest accumulations within 24 x 24 km squares

Figure 20 shows the highest accumulations (on 4-km pixels) to have occurred within 24 x 24 km squares from 12 to 18 UTC. It reveals that very high accumulations of more than 60-70 mm were predicted close to Boscastle. The idea of displaying the accumulations on larger squares is to indicate that high accumulations are possible in particular areas, but at the same time we can not believe the precise model grid-square predictions. The choice of a size of square to use for such a diagnostic should very much depend on the spatial skill of the model - but that has to be determined. It should also depend on the predictability of a particular meteorological situation - a difficult, but interesting problem. Clearly, if a larger square had been used the pictures might have looked better in that Boscastle would be within a red area, but then the product would be less discriminating.

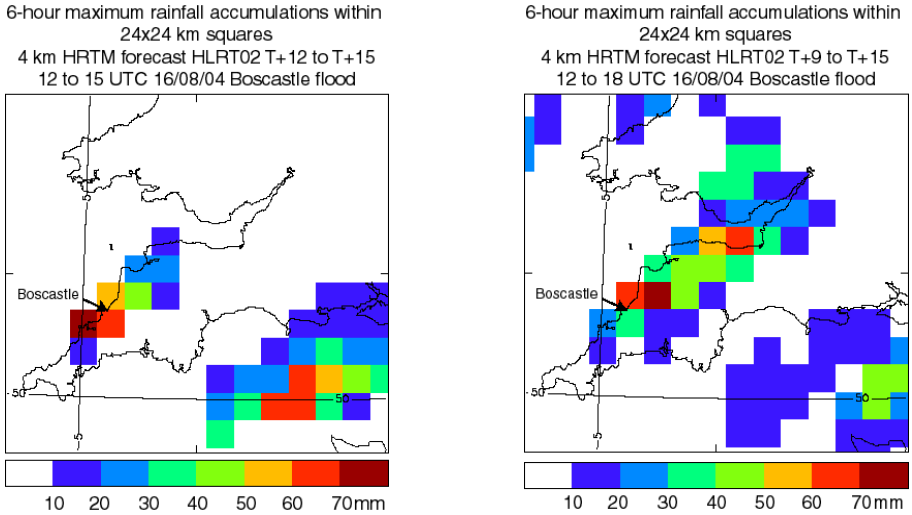



**Figure 20 Forecast maximum 4 km accumulations over 24 km squares. 1200-1500 UTC from 0000 UTC (left), 1200-1800 UTC from 0300 UTC (right).**

### 3.4.4 Extreme accumulations within 24 x 24 km squares

Figure 21 aims to give an indication of the extreme maximum accumulations that may occur given the 4-km model precipitation forecast. At short intervals (every time step or few minutes) the rainfall rates are converted into accumulations. Then a cell detection algorithm is used to join areas of rain together. Once individual rain areas/showers are known the accumulations are adjusted to take account of the possibility that the highest accumulations within a particular shower could occur elsewhere within that shower (within a defined radius). The method should pick out situations where rain areas are slow moving and there is the possibility of very high totals falling in some locations. The information is displayed on 24x24 km squares for the same reason as before - to take account of our uncertainty in the grid-scale prediction of the rain.

The picture does give an indication that very high rainfall totals were possible (>80mm) in the region close to Boscastle (and >160mm a few kilometres away). The product could be used to give a warning that an extreme event may occur. Some caution must be taken in the interpretation though - it is meant to be a extreme, so on most occasions it will not happen and for that reason will be very difficult to verify. Nevertheless, that the total of >160mm is close to that reported from rain gauges is interesting.

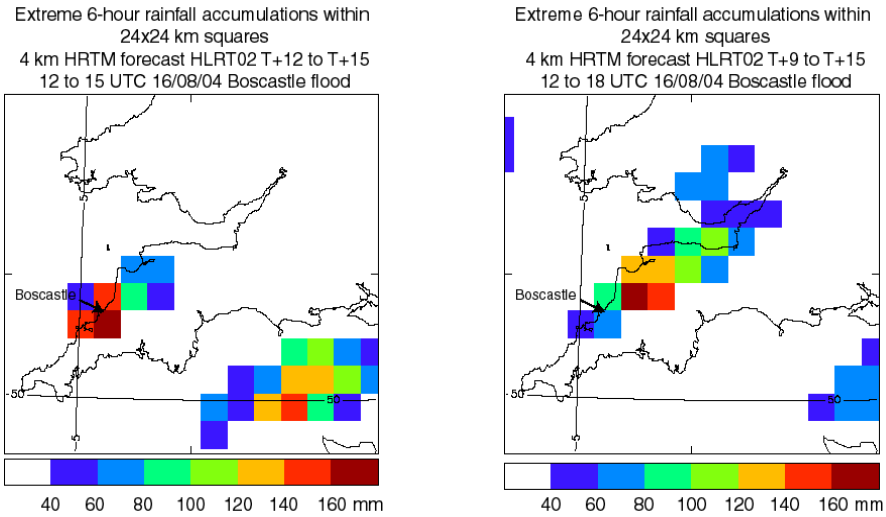



**Figure 21 Forecast extreme accumulations in a 4 km box, 1200-1500 UTC from 0000 UTC (left) and 1200-1800 UTC from 0300 UTC (right).**

## 3.5 Mechanism

The 4 km model was both remarkably accurate and quite consistent, at least in the region of triggering, between forecasts. This suggests a high level of predictability, which further suggests that a strong surface influence (i.e. land/sea contrast, orography and land surface cover) is likely, as these inputs are quite well known.

Figure 22 shows the forecast 10 m wind and its convergence at 09, 10 and 11 UTC, i.e. in the few hours before precipitation first formed. The first precipitation formed to the SW of Boscastle. The figure shows divergence over the sea, and convergence over the land along the N Cornish coast, modulated by the orography. The low level flow is southerly over land while to the north the flow is closer to the geostrophic south westerly. The convergence is stronger on the NE (leeward) side of hills. Strong low level convergence formed in the region of the Camel valley where rain initiated both in the model and in reality. Strong convergence also happened elsewhere, later associated with rain and largely lined up with the cell movement direction. The 12 km model (Fig. 23) shows only a very weak coastal convergence and no strong local 'hot spots', though the strongest convergence even in this model is over the Boscastle area and over Lynmouth.

Figure 24 shows the sensible heat flux. This significant over land, as would be expected, but does not show a great deal of geographical variation. The main variation is a tendency for higher fluxes (by a few 10s of W $m^{-2}$) over the high ground, consistent with ideas of elevated radiative surface heating. Essentially, the surface energy balance is dominated by temperature, and is only weakly dependent on altitude. Surface temperatures are similar at altitude compared with low down, but the air temperature is colder (by adiabatic cooling), leading to a larger temperature difference so a larger sensible heat flux. The pattern is not strong enough to directly explain the convergence pattern, though it may have contributed to stability effects. We therefore postulate that land/sea roughness contrast and overall thermal contrast dominated the coastal convergence, modulated strongly by local orography. This requires further work to confirm.

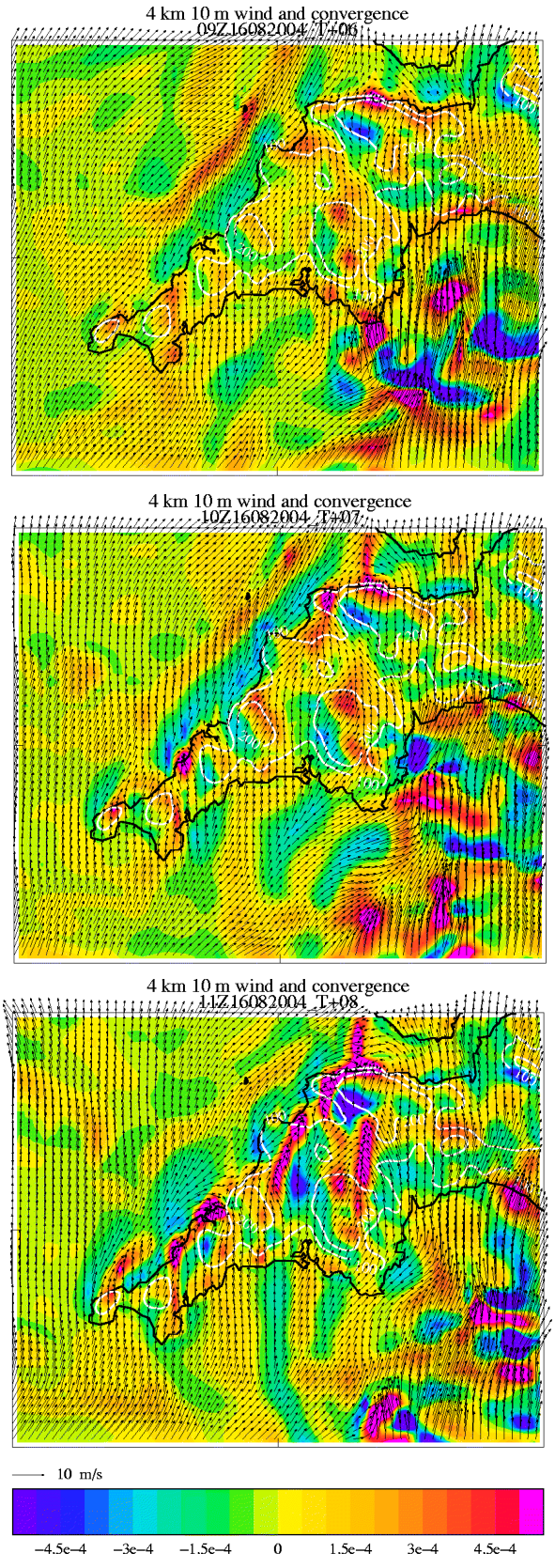



Figure 22 Forecast 10 m wind and convergence of 10 m wind (colours) from 0300 UTC run, at 0900, 1000 and 1100 UTC (top to bottom). Orography shown as white contours.

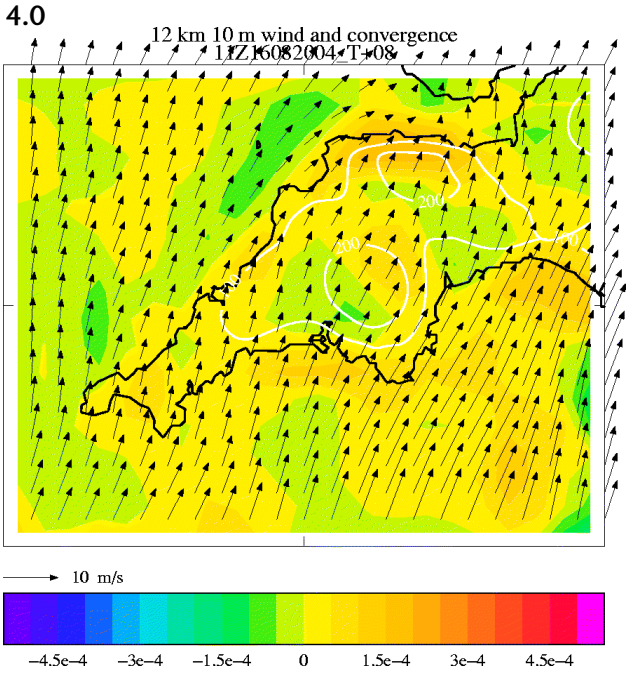



Figure 23 Forecast 10 m wind and convergence of 10 m wind (colours) from 0300 UTC 12 km run, at 1100 UTC. Orography shown as white contours.

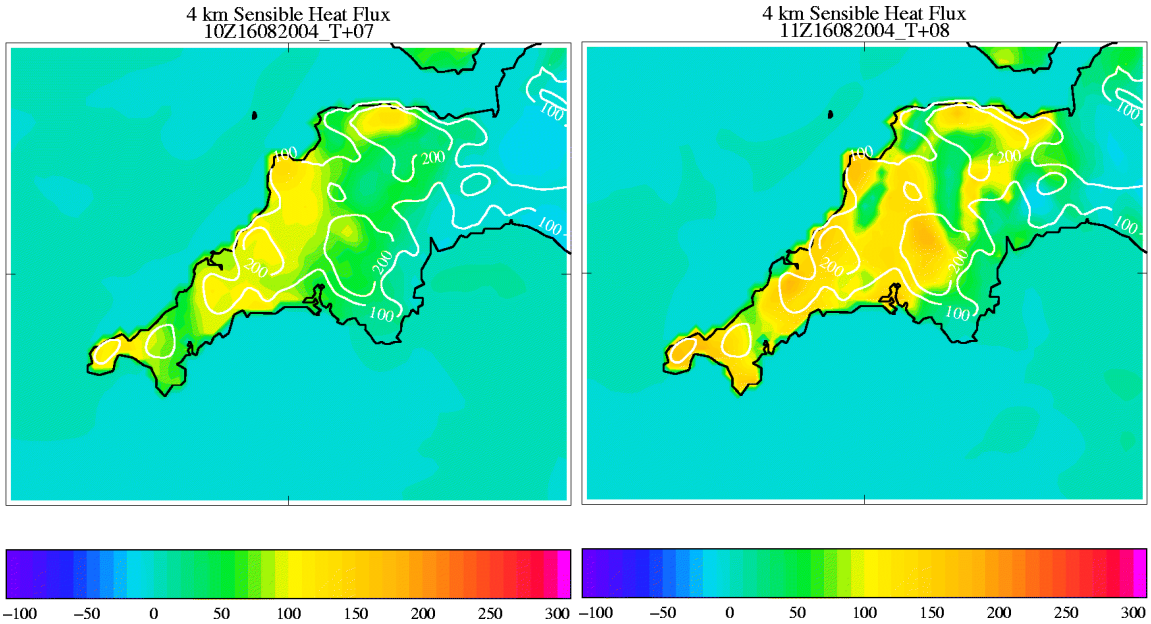



Figure 24 Forecast sensible heat flux in 4 km model at 1000 UTC (left) and 1100 UTC (right) from 0300 UTC run.

## 4.1 Preliminary comments

In order to look at the river flow for this flood event Vicky Bell of CEH, Wallingford agreed to rerun off-line the river flow component of the operational system using retrieved runoff from Nimrod-MOSES-PDM. Much of the material on river flow presented here was produced by Vicky Bell.

## 4.2 Surface runoff in north Cornwall during the afternoon of 16 August 2004

The surface runoff produced by MOSES-PDM from the rainfall analyses in the period 1300 to 1700 UTC is shown in Figures 25(i)-(iv).

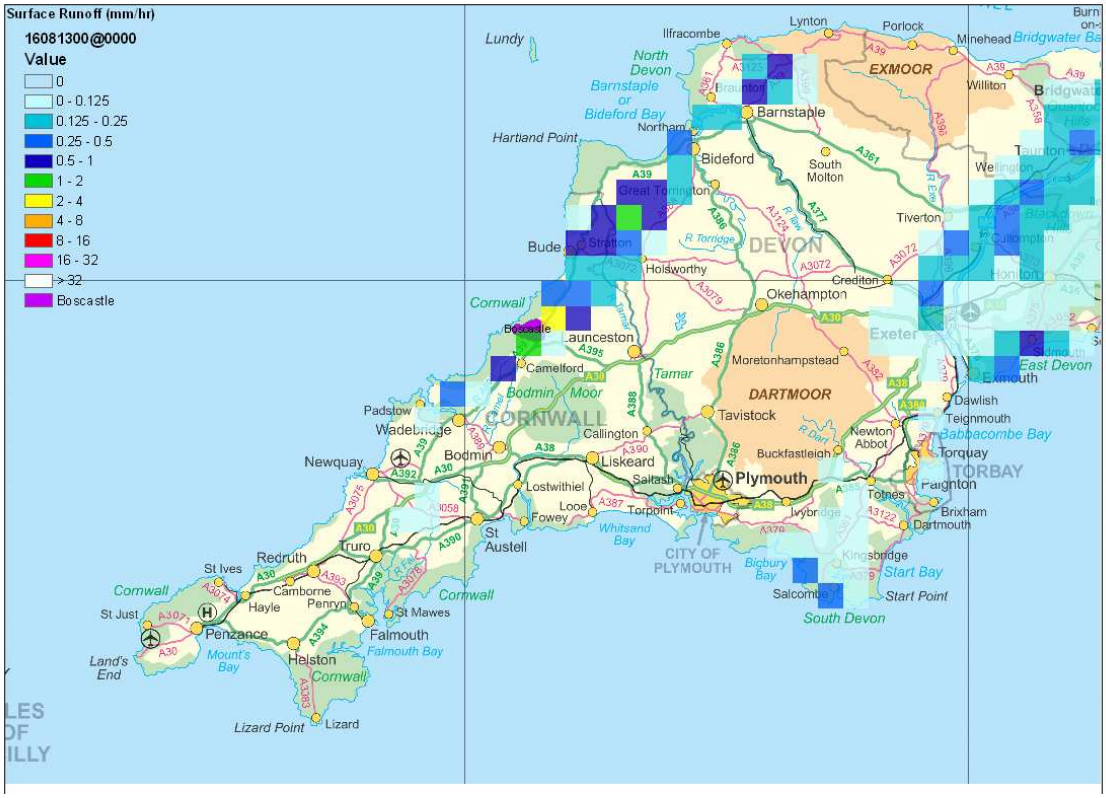



Figure 25(i). Surface runoff from Nimrod-MOSES-PDM during 1300-1400 UTC

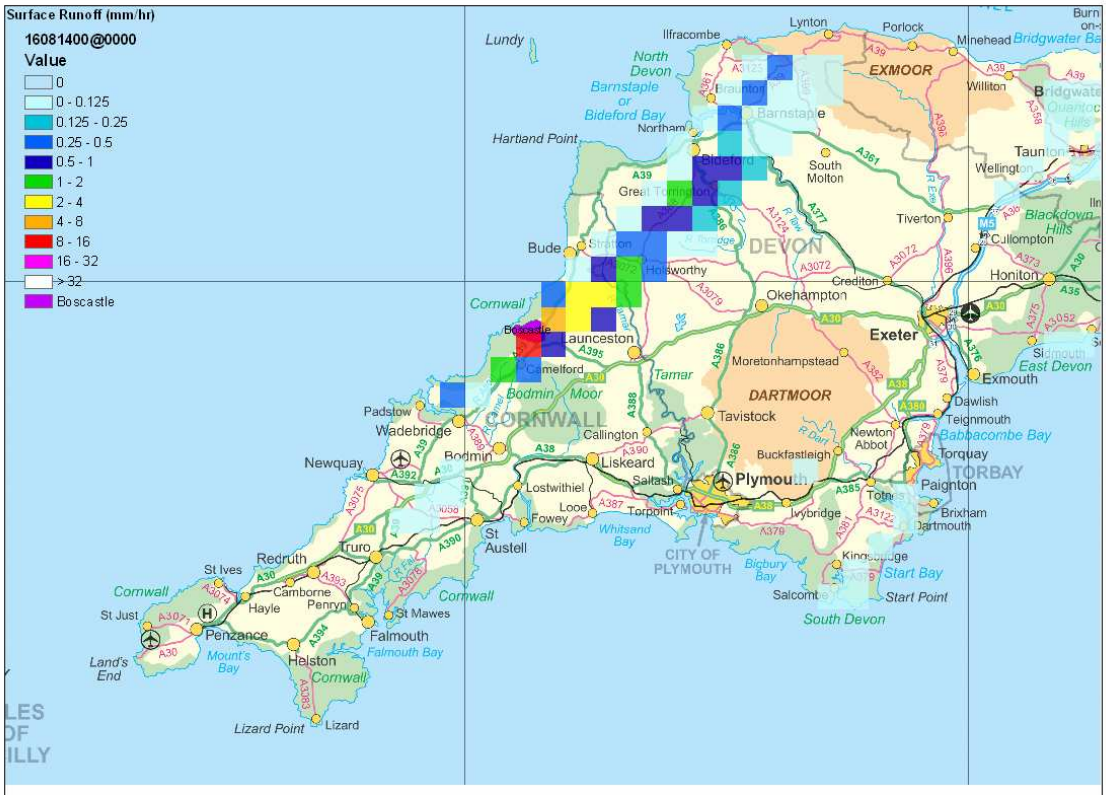



Figure 25(ii). Surface runoff from Nimrod-MOSES-PDM during 1400-1500 UTC

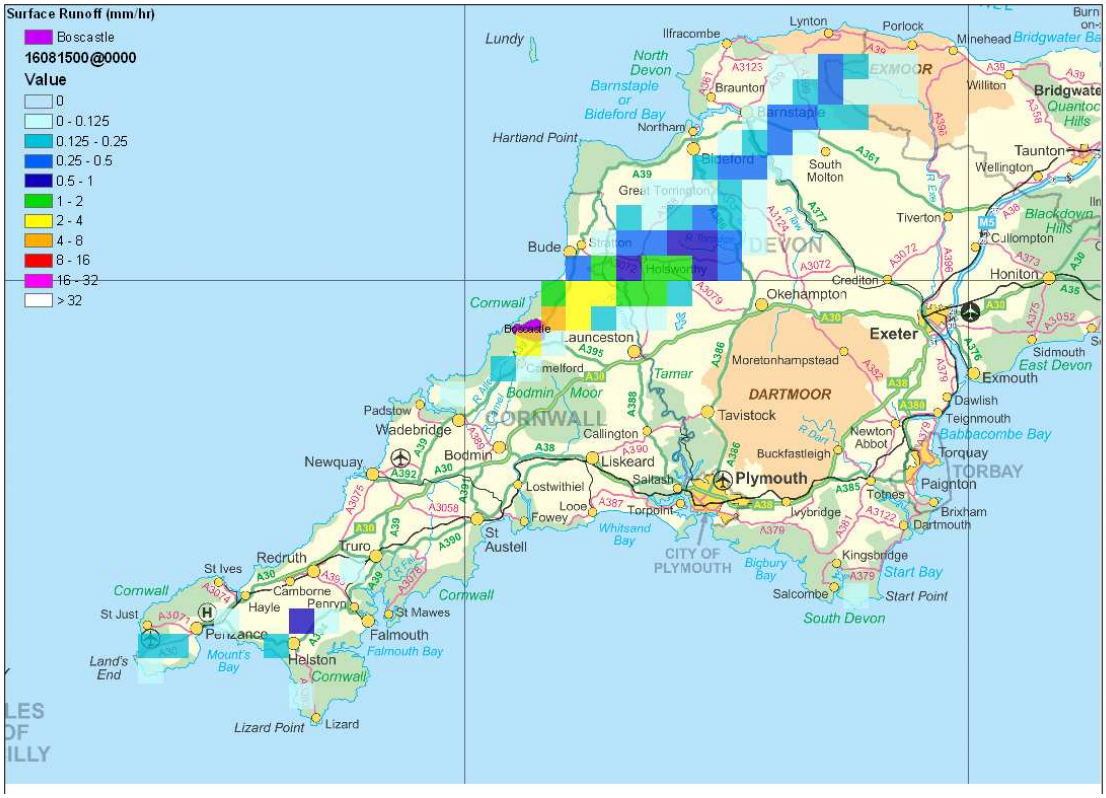



Figure 25(iii). Surface runoff from Nimrod-MOSES-PDM during 1500-1600 UTC

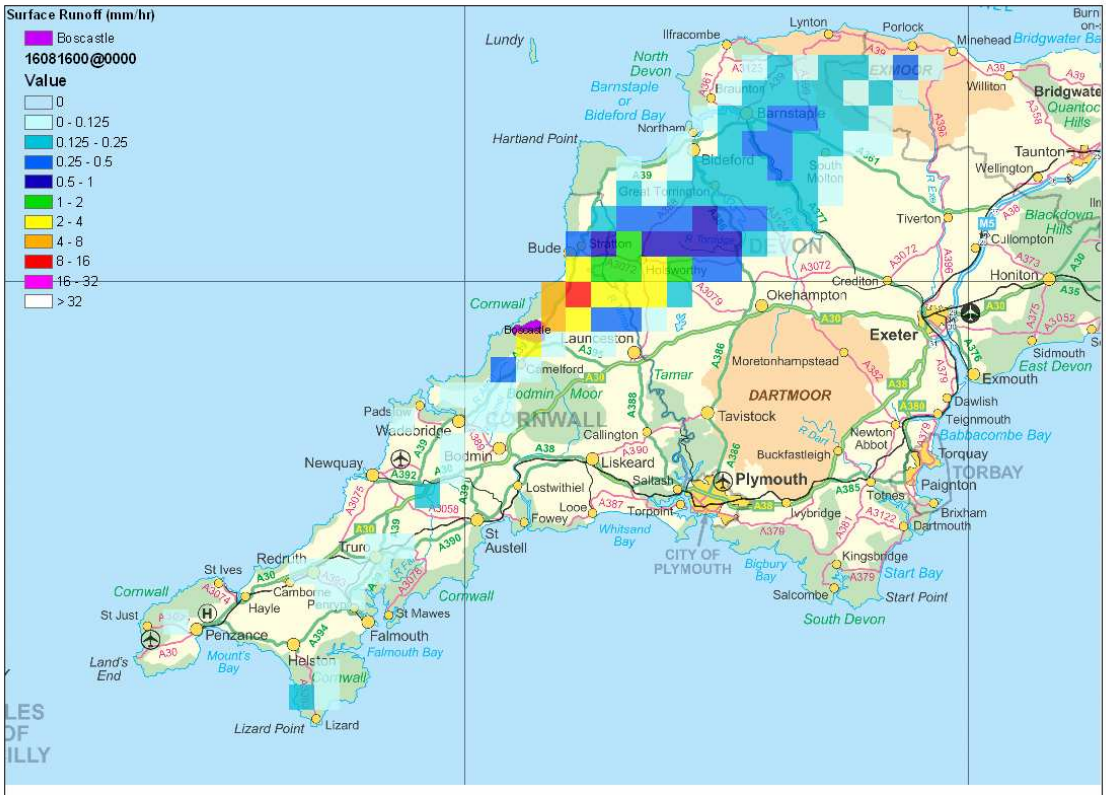



**Figure 25(iv). Surface runoff from Nimrod-MOSES-PDM during 1600-1700 UTC**

No measurements of runoff are made and so it is not possible to verify it directly. However, it is likely that in areas of steep terrain, such as the coast of north Cornwall, insufficient surface runoff is produced because of the spatially uniform value of the B parameter in the PDM. This was reduced to a value of 0.5 earlier in the year (from a uniform value of 1.0) on the recommendation of CEH. It is known that in areas of steep terrain a higher value of B is usually appropriate, giving more surface runoff.

## 4.3 River flow in the Boscastle catchment

The rivers draining to Boscastle are ungauged, and the definitive catchment area is unknown. However, estimates of area based on digital terrain data (FEH CD-ROM) indicate it is of the order of 20km$^2$ (see Figure 26(i)). Because of the small size of the catchment the accurate delineation of the catchment boundary using a 1km DTM is very challenging. The boundary based on the Hydro1k DTM (20km$^2$) is shown with a red line in Figure 26(ii). An alternative boundary derived from another 1km DTM (based on OS data) is shown with a green line (26km$^2$).

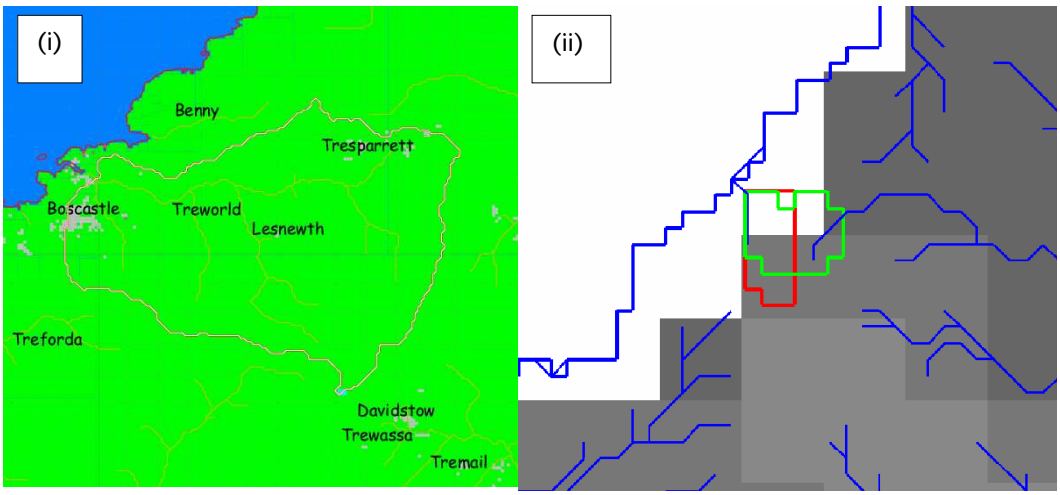



**Figure 26. Catchment delineation for Boscastle. (i) Map of the catchment obtained using the CEH FEH CD-ROM; (ii) Catchment boundaries derived from 1km DTMs. The Nimrod catchment boundary derived from Hydro1k DTM is shown in red; a boundary derived from an alternative 1k resolution DTM based on OS 1:50,000 elevation data is shown in green. Blue lines represent rivers derived from the Hydro1k DTM (drainage area > 5km$^2$). The grey squares are Nimrod land grid squares. NB Different scales in Figures 26(i) and 26(ii).**

It is clear that the catchment based on the Hydro1k DTM used in the operational Nimrod system is not a good representation when compared with the available representation of reality shown in Figure 26(i). The alternative boundary based on a DTM derived from OS data (and probably the river courses based on that data too) is closer to reality because of its greater eastward extent.

The most striking fact which can be seen in Figure 26(ii), however, is the very poor representation of the coastline by the Nimrod 5km land-sea mask. Nearly half of the catchment on the 1km grid is 'sea'. The water balance of the catchment is therefore affected by the Nimrod 5km land-sea mask which cuts through the catchment. Only 11km$^2$ of the catchment appears to lie within the land-sea mask.

The Environment Agency have already noted the poor land-sea mask for Nimrod-MOSES-PDM products after seeing example Hyrad displays produced for them by CEH. See Appendix A for a more widespread comparison of the Nimrod land-sea mask with reality as displayed on Hyrad.

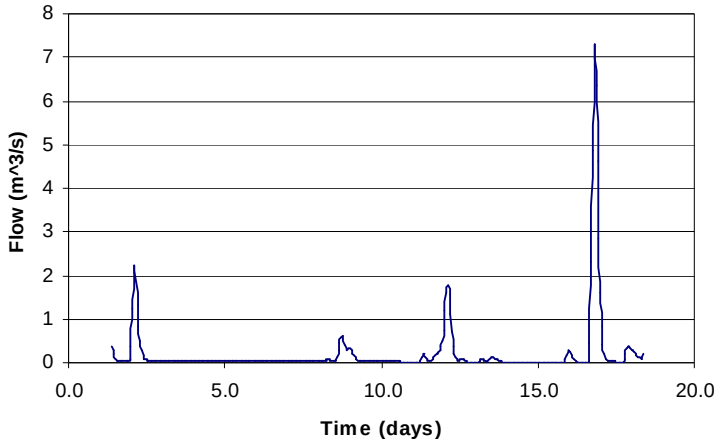
Figure 27 presents time series of modelled river flow, width and depth for the period 0900UTC 1 August 2004 to 0900UTC 18 August 2004. Because the Nimrod runoff data only cover a fraction of the catchment, a crude attempt has been made to correct the water-balance by multiplying the Nimrod runoff for the catchment by a factor of 1.8. Time-series plots adjusted in this way are shown in Figure 28.

The estimated river characteristics derived from the formulae given by Bell and Moore (2004) are as follows:

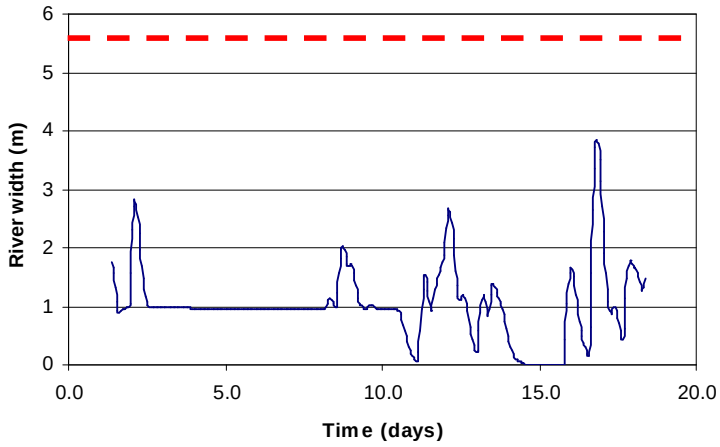
Bank full discharge: 32.4 $\mathbf{m^3s^{-1}}$
Mean annual discharge: 0.362 $\mathbf{m^3s^{-1}}$
Bank full depth: 0.87 m
Bank full width: 5.67m

The absolute modelled river flow will have been affected by inadequate conversion of rainfall to surface runoff and by the land-sea mask problem (although the latter has been corrected for in Figure 28). The modelled flow, width and depth do not reach the estimated bank full values even in the 'corrected' Figure 28. It is thought that the small Boscastle catchment does not fit the formulae of Bell and Moore very well. The formulae were calibrated to fit UK data but a large amount of scatter remained. It is not known what the bank full values were in reality.

(a) Modelled flow for the estimated catchment to Boscastle




(b) Modelled river width




(c) Modelled river depth

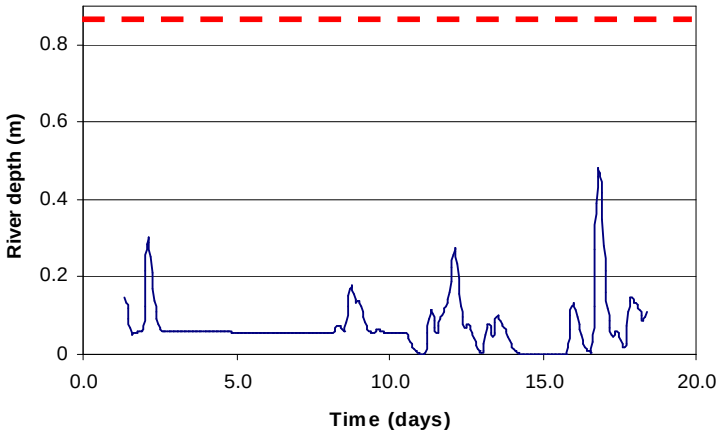
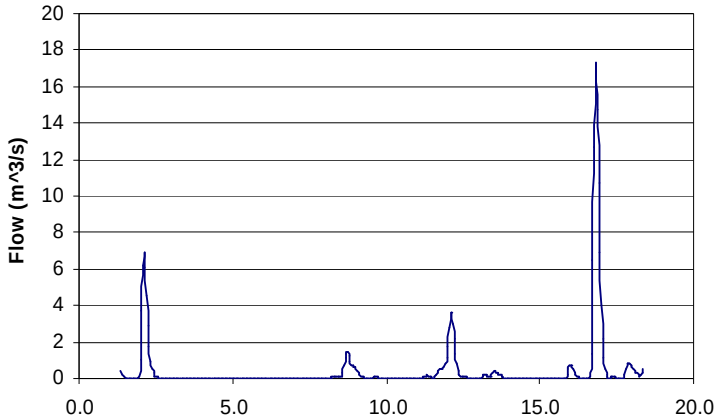
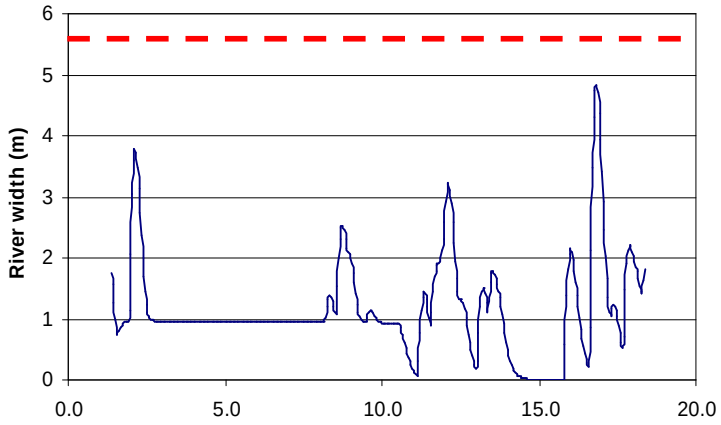



Figure 27. Modelled river flow, width and depth for the estimated catchment draining to Boscastle. Estimated bank full values of depth and width are shown with a dashed red line.

(a) Modelled flow (with adjustments made for the area of Nimrod land-sea overlay) for the estimated catchment to Boscastle




(b) Modelled river width




(c) Modelled river depth

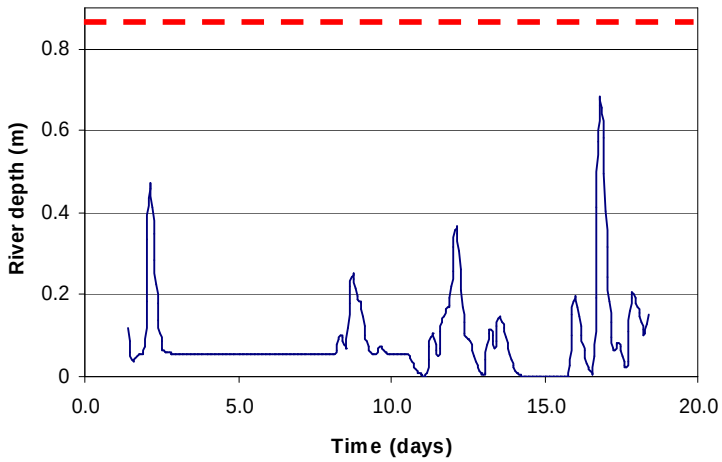



Figure 28. Modelled flow, river width and depth for the estimated catchment draining to Boscastle. An areal adjustment factor of 1.8 has been applied to runoff values to correct for the Nimrod 5km land-sea mask cutting through the catchment. Bank full values of depth and width are shown with a dashed red line.

## 5.0 Conclusions

- Observations show that maximum precipitation reaching twice the monthly average rainfall for North Cornwall, was observed in a narrow strip of about 4km by 10km. Due to its intensity and very small size, this event was an extreme test of Met Office operational and experimental precipitation forecasting systems.

- The Nimrod and Gandolf nowcast schemes failed to adequately predict the event because it did not fit the pattern of a rain band or rain cells moving unchanged with constant velocity. Rather, the situation was characterised by continual development of new cells, a process for which nowcasting methods are not suited. In Nimrod and Gandolf, such development is included by merging downscaled information from the mesoscale NWP model, a process which is normally very successful in extending the useful forecast period. However, on this occasion, the event was too small to be resolved by the NWP model.

- The new, STEPS, ensemble nowcast provided few advantages over Gandolf and Nimrod nowcasts for the same reasons that Nimrod and Gandolf performed poorly. The incorporation of a stochastic, convective initiation and life cycle model algorithm into STEPS, similar to that implemented in the Convection Diagnosis Procedure (CDP), may go some way towards the effective handling of extreme, yet very localised events such as that which occurred in the vicinity of Boscastle on the 16 August 2004. The vast majority of fluvial flood events are caused by much larger scale pluvial events than that which occurred on 16 August 2004. For example, the Easter floods of 1998 were associated with a broad band of slow moving precipitation containing numerous embedded, intense precipitation cores associated with convective cells. STEPS can be expected to add significant value to mesoscale NWP output in these more common flood producing precipitation events.

- The Convection Diagnosis Procedure (CDP) provided useful guidance on the structure of the convection. However, the outputs need careful interpretation and the signal for the rainfall rates was weak.

- A 4-km grid length mesoscale NWP simulation was able to generate storms that produced high rainfall accumulations remarkably close to where they occurred, when the equivalent 12-km operational forecast was unable to give any direct warning of such an event. The reason the 4-km model could do this was because it could explicitly resolve the thunderstorms instead of having to rely on a convection scheme, and, equally importantly, was able to resolve the complex flow around the coast which lead to repeated triggering of storms in the same place. Two successive forecasts produced very consistent results, though the first was better. This suggests that the event had a high degree of predictability but small scale uncertainty was still enough to make the forecast unreliable at the scale of the Boscastle catchment.

- A 1-km grid length forecast produced an even better location for the high accumulations because it was able to resolve the showers and the local orography more accurately. Lower (though still high) accumulations were produced than the 4 km model, which reflects a known problem with the 4 km model.

- The mesoscale NWP model confirms that the interpretation of the mechanism leading to such spatial localisation publicised at the time appears to be substantially correct. This mechanism involves strong low level convergence at the coast due to land-sea roughness and thermal contrast, modulated strongly by local orography, leading to a very specific and repeating location for triggering of storms.

- The output from the 4-km mesoscale NWP forecast represents a specific realisation of the event, which we know is going to be in error to some extent. If we took the later, 03 UTC, forecast literally it would warn of the high rainfall totals falling into a different river catchment to the one it did fall into. It is possible to be misled into believing the detail unless we have a good understanding of the uncertainty in NWP forecasts. Since many customers do not have that appreciation, it is vital that we present the output in a way that shows some uncertainty yet picks out the more reliable and important information.

- The mesoscale NWP products shown in Section 4 of this report show that the model was suggesting a risk of high rainfall totals but without being specific about exactly where the rain would occur. At best, a warning of flash flooding in the N Cornwall and N Devon areas could have been supported. Two issues that need addressing are (1) how we determine the spatial accuracy of precipitation forecasts so that diagnostic products can be tuned to those scales and (2) whether there are ways of determining how predictable forecasts are likely to be on a particular day (beyond use of expensive ensembles). On this occasion, it is likely that the storms were reasonably predictable because there was a strong coastal and orographic component to the forcing. On other days, however, the atmosphere may be much less predictable. We would like to have products that reflect this.

- This event has added weight to the belief that an NWP model with 4-km grid length or better, with appropriate output products, has the potential to provide significantly more useful short-range predictions of high-impact rainfall events than is currently possible.

- There is a need to clarify the relationship among the different very short range nowcasting and forecasting schemes to ensure that the most appropriate outputs are used. High resolution NWP will not meet this need alone.

## 6.0 Recommendations

- A stochastic convective initiation and life cycle model algorithm, similar to that implemented in the Convection Diagnosis Procedure (CDP), should be incorporated into STEPS. This may go some way towards the effective handling of extreme, yet very localised events.

- Outputs from the Convection Diagnosis Procedure (CDP) should be reviewed to ensure that the products are useful to forecasters.

- 'High resolution' NWP is able to produce realistic convective storms which respond to surface forcing and give more useful indication of peak rainfall than parameterized convection in lower resolution models. 4 km is only a marginally adequate resolution, while 1 km is a worthwhile target resolution. High resolution NWP should therefore be adopted as soon as resources allow.

- A post-processing system for high resolution NWP needs to be developed to provide appropriate risk-based inputs to downstream flood warning processes. This should be in the form of probabilistic guidance which allows for the positional and developmental uncertainties inherent in model forecasts.

- Longer trials of NWP systems are required to calibrate post-processing systems.

- A new post-processing system is required to rationalise the capability currently provided by Nimrod, Gandolf and CDP systems. It may be appropriate to introduce this with the implementation of the 4km UK NWP model in 2005.

- Introducing a spatially varying B parameter, depending on at least a topographic index, should be considered as a development task for Nimrod-MOSES-PDM.

- A more accurate 5km land-sea mask should be sought for Nimrod. The original code for generating the land-sea mask should be checked for correct registration of the AVHRR data and the criterion for a land Nimrod square should be changed from 50% of land in the square to a lower value, perhaps 25%.

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